Planning and Policy Implementation Strategies for Green Stormwater Best Management Practices in the Proctor Creek Watershed, Atlanta, Ga.

Option Paper
Requirements for the City and Regional Planning Master's Degree
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“Water runoff can be a significant problem in urban areas for two primary reasons. First, impermeable surfaces of the Concretion System affect the flow of water so that it is more rapid, does not soak into the ground, and concentrates in different ways than without them. Second, stormwater runoff in particular can cause pollution at outfall locations” (Campbell and Corley 2012, 164).

Introduction

Environmental Conditions

In the Proctor Creek watershed, stormwater issues have far-ranging social, economic and environmental impacts. The headwaters to the Proctor Creek watershed are located in downtown Atlanta, extending northwest where it empties into the Chattahoochee River. This watershed encompasses an area of 23 miles and is home to almost 52,000 residents in 38 neighborhoods (About Proctor Creek 2014). The creek has traditionally been a point of pride for the community, but in recent years has been degraded into a perpetual dumping ground associated with disease and flooding (Proctor Creek Stewardship Council 2014). This alteration in perception is due to widespread illegal tire dumping activity (City of Atlanta 2012), severe inundation of neighborhoods (Atlanta Journal Constitution 2011), and combined sewer overflow (CSO) events dumping sewage directly into the creek (The Washington Times 2014, Creative Loafing 2001).

These issues were recognized on a national scale when the Proctor Creek watershed was designated as one of 18 communities nationwide participating in the Urban Federal Waters Partnership. While the partnership's goal of "reconnect[ing] urban communities, particularly those that are overburdened or economically distressed, with their waterways" is honorable, the fact that this community meets these undesirable qualities underscores the level of severity of the environmental degradation in this watershed (EPA Urban Waters 2013).

Purpose of this Paper

The purpose of this paper is to provide policy recommendations that inform an effective implementation strategy for small-scale green infrastructure projects in the Proctor Creek watershed, thereby reducing the environmental issues of pollution and flooding.

To start, this paper will clearly identify the major environmental issues in the watershed. The literature review will then identify the origin of these issues in land development patterns and their accompanying stormwater management practices. The hydrologic dynamics of the current stormwater best management practices (BMPs) will be explained to demonstrate how reductions in volume at the source improve water quality. Those stormwater BMPs that best reduce volume will be defined, and design characteristics suitable to the Proctor Creek watershed will be prescribed, enabling an accurate estimation of volume reductions to be assigned for each BMP. A document review will then be performed in order to analyze the following stormwater BMP implementation strategies: regulatory post-development stormwater ordinances, stormwater retention credit trading programs, and targeted combined sewer relief plans.

The implementation strategies and stormwater BMP volume reduction estimations will provide the basis for scenarios that will be modeled in the methodology section of the paper. A stormwater runoff model will be created using ArcGIS and the EPA's BMP siting and optimization tool SUSTAIN. Measurements of runoff volume reduction will be recorded and analyzed to create informed policy recommendations for small-scale stormwater MP implementation. These recommendations will aim to answer the following questions:

1) Is the stormwater runoff primarily due to large amounts of directly connected impervious surfaces? If so, what BMPs will reduce the stormwater runoff?
2) What are the best policy based implementation strategies that Atlanta can adopt in order to reduce stormwater runoff?
3) What policy recommendations can be derived from the modeling of different Green Stormwater BMP implementation scenarios?

Overview of Issues

"Stormwater runoff quantity and quality can adversely affect public safety, public and private property … recreation, aquatic life, property values and other uses of lands and waters" (Code of

Ordinances. Chap. 74, art. X 2013). These adverse impacts are experienced within the Proctor Creek watershed and are linked to the issues of sedimentation, flooding, and *E. coli* pollution.

Sediments are particulate matter, organic and inorganic, that are transported by, suspended in, or deposited by water (EPA Office of Water 2014). Sedimentation occurs when sediments are deposited in the creek bed in a way that alters the natural flow of water, causing stream erosion and bank destabilization. These alterations disrupt the natural habitat, which reduces the biological productivity and weakens the ecosystem's resiliency. The harm to the creeks ecology is exacerbated when trace pollutants that are carried with sediments settle out of the water column, exposing biota to accumulating toxins and increasing the biota's susceptibility to diseases (Georgia Adopt-A-Stream 2009). Since Proctor Creek is classified as a recreational and fishing water body, both the presence of toxins in the creek and the reduced biologic productivity of the ecosystem can reduce the utility that residents receive from the creek.

Many of the neighborhoods in the headwaters of the Proctor Creek watershed have reported instances of parcels, buildings, and homes being inundated during severe storms causing both direct and indirect economic damages. Inundated buildings are extremely costly to repair, resulting in financial hardships for the property owners and the possibility of buildings falling into disrepair. Those buildings that fall into disrepair can become blighted, reducing the property values of the surrounding parcels. This inundation-disrepair-blight cycle has been occurring for several decades, complicating redevelopment efforts as property ownership rights become muddled over time (Park Pride 2010).

The previously discussed issues associated with alterations to the water flow are intensified by the presence of *E. coli* bacteria, which are associated with organic matter, including human waste. High levels of organic matter in the stream may cause eutrophication in the creek, negatively impacting the ecology of the creek by reducing the amount of dissolved oxygen available to biota (Georgia Adopt-A-

Stream 2009). High levels of *E. coli* are also used as proxies for other bacteria that cause diseases such a hepatitis A and cholera, both of which can cause dehydration leading to death (EPA Office of Water 2008). To reduce the risk of exposure, the EPA recommends persons avoid contact with *E. coli* polluted waters, which a difficult challenge when flooding waters mix with sewage (EPA Office of Water 2008).

The negative impacts of these issues shifted the way residents of the watershed perceive Proctor Creek. What was once a source of recreation and enjoyment is now to a threat to their quality of life.

Policies in the Proctor Creek Watershed

The Urban Federal Waters Partnership is the latest in a long list of planning and policy initiatives that are in place in the Proctor Creek watershed, with the most influential of these initiatives being the Clean Water Act (CWA). The goal of the CWA is to eliminate or reduce pollutants discharged into the watershed to a level that maintains the chemical, physical and biological integrity of the waters to allow for protection and propagation of wildlife and provide recreation in and on the water. In the Proctor Creek watershed, the CWA has been responsible for establishing the “Total Daily Maximum Load” of pollutants allowed in the creek, regulating the amount of point source pollutants discharged to the creek, and identifying and characterizing possible non-point sources of pollution (U.S. Code 1972).

The CWA established a National Pollutant Discharge Elimination System (NPDES) that requires the Georgia Environmental Protection Division (EPD) to manage and enforce a statewide point source pollution permit program (U.S. Code 1972). In the 1990’s, the City of Atlanta was sued for contributing to the impairment of the Chattahoochee River, with a large portion of the pollution coming from the NPDES permitted combined sewer system. When heavy rainfall events occurred, the combined sewer system would exceed capacity, causing CSO events that discharged waste- and storm-water into Proctor Creek. From this lawsuit, the City agreed to a consent decree resulting in a long-term control plan, which reduced the number of CSO events to no more the 4 per year in the Proctor Creek watershed

(Department of Public Works 2002). This reduction shows the effectiveness of the current regulations in place to reduce point source pollution.

The CWA also enables the EPA to provide grants, which are used to incentivize the creation and implementation of a Watershed Improvement Plan (WIP) (U.S. Code 1972). The WIP for Proctor Creek used targeted monitoring to characterize the pollution in the creek; aiding the identification of possible sources of non-point source pollution (Atlanta Regional Commission 2011). This plan recommended large, visible green infrastructure projects that mitigate flooding and pollution by reducing the volume of stormwater runoff such as the Boone Boulevard Green Street and Lindsay Street Park. Similar projects have been recommended in other plans and are accompanied by a wide variety of funding mechanisms (Wheatley 2014, Park Pride 2010, Trust for Public Land 2014).

However, the current trend in mitigating water-borne environmental degradation is to mimic the natural hydrology of the watershed, through techniques labeled green infrastructure. The primary way the natural hydrology is affected by urban areas is through increased impervious surface at the site development level. Therefore widely distributed small-scale projects must also be implemented alongside the large-scale infrastructure improvements to address the issues at their source. To implement these types of projects, the City of Atlanta passed an Amendment to the Post-Development Stormwater Ordinance requiring every land development activity be accompanied by an on-site green infrastructure project (City of Atlanta 2013). While the potential impact of this ordinance could internalize many of the negative impacts land development has on stormwater runoff, the effectiveness of this implementation strategy is unclear. The following literature will further explore the relationship between land development and issues of stormwater runoff, with an emphasis on historical stormwater BMPs that have contributed and remedied past and present water quality conditions.

Literature Review

Overview

This literature review begins with an explanation of the history of land development, and associated stormwater management techniques, within the Proctor Creek watershed. The current stormwater BMPs will then be analyzed, accompanied by an explanation on how the hydrological dynamics these BMPs improve water quality by reducing stormwater runoff volume. Strategies for implementing stormwater BMPs will then be described, with the following policies advancing in complexity: regulatory post-development stormwater ordinances, stormwater retention credit trading programs, and targeted combined sewer relief plans. This literature review will inform the scenarios created in the subsequent methodology and modeling section of the paper.

Stormwater Management Techniques

Over time, advancements in technology have reframed the way professionals view stormwater issues and established new methodologies for managing stormwater runoff. Throughout this evolution, methods for managing stormwater runoff have always been in response to land development patterns. Therefore, historical land development patterns within the Proctor Creek watershed will be used to contextualize the evolution of the following stormwater management techniques: conveyance of water and filth away from the city core; detaining the runoff to reduce flooding; and protecting the health of the creek through monitoring water quality.

Conveyance of water and pollution

The City of Atlanta was first founded in 1836 as a terminus for railroads. This location was considered suitable because it is located along the most southern ridgeline of the Smokey Mountains, forming the least cost path between the Atlantic Ocean and the Mississippi River in the Southeast. Consequently, the City of Atlanta developed around this central terminus, placing the core of the city at the highest elevations in the Proctor Creek watershed. Engineers used this elevation difference to convey storm and waste water away from the city core through the use of ditches (Reese 2001).

In the 1870's streetcars were introduced, allowing for people to move out of the core of the city. This sprawling of the population led to health concerns, as neighborhoods built at the outfalls of the ditch conveyance systems exposed an increasing number of residents to exposed sewage. This caused Atlanta's Board of Health to adopt the first plan for a sewer system in 1888. The sewage system used stormwater to transport the waste from the downtown area to one of five trunk sewers. Treatment plants were built at the outfalls of these sewer trunks in 1910; one of which in the Proctor Creek watershed (Mitchell 2010).

As the downtown core of the city expanded in the 1900's, large swaths of land was developed, replacing natural ground cover with impervious surfaces. This high percentage of impervious cover alters the natural hydrology by increasing both the volume and velocity of the stormwater runoff, which is conveyed to the combined sewer system (CSS). When volume exceeds the capacity of the CSS, the treatment facilities are overloaded, and discharge wastewater directly into a water body (Figure 1).

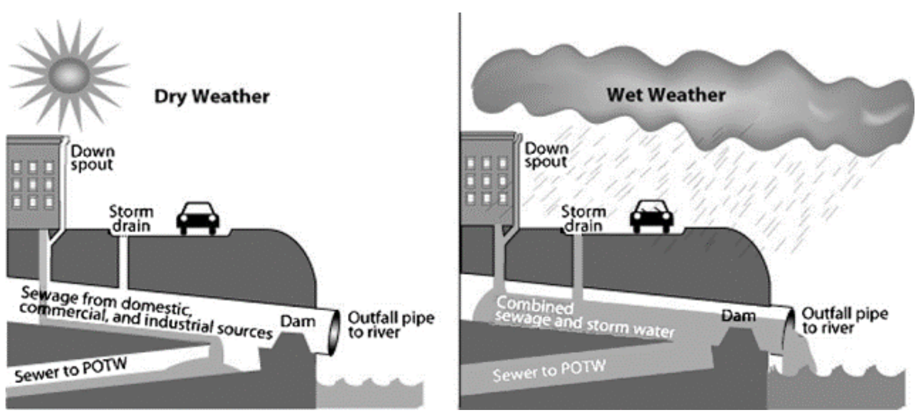


Figure 1: Diagram of Combined Sewer Overflows
http://water.epa.gov/

One of the following interventions can be used remedy these combined sewer overflow (CSO) events in the Proctor Creek watershed: 1) increase capacity in the CSS; 2) increase capacity of treatment plants; or 3) separate the waste water from the storm water. The CSS capacity has been expanded through many projects, the most drastic of which are the large underground sewage storage tunnels built in the early 2000's (Department of Public Works 2002). The capacity of treatment facilities has been expanded by implementing new technologies that increase the size and speed of the Combined Sewer treatment facilities. As water quality regulations became more stringent, increased technology fees made treating sewage expensive. These exorbitant costs were used to justify separating portions of the combined sewer system into storm and sanitary sewer systems (Department of Public Works 2002). These separated sewer systems caused unforeseen stormwater issues which facilitated the creation of drastically different techniques for stormwater management.

Reduce flooding by detaining water:

Atlanta's Municipal Separated Storm Sewer System (MS4) is designed to quickly convey stormwater away from inundated areas. This became problematic as the sprawling trends of the 1900's continued, whereby large volumes of runoff were generated by a highly impervious downtown area and conveyed to streams surrounded by neighborhoods. These high velocities and volumes at major outflow locations caused stream erosion and inundation in communities surrounding the city core.

These issues were transferred into engineering problems through the use of hydrographs, which visually display the rate of water flow against time at a specific point in the creek. Engineers used the hydrograph to decrease flooding by reducing the peak discharge rates during storm events (Figure 2). This was accomplished by detaining the water in ponds, then releasing it over an extended period of time (Reese 2001).

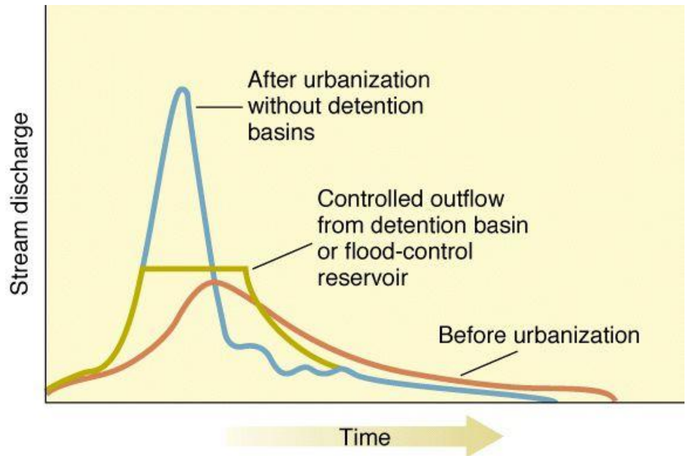


Figure 2: Effect of Urbanization on Stormwater Runoff
geogonline.org.uk

Using detention ponds as the primary stormwater management technique has major shortcomings. Detention ponds are designed to solve the peak flow problems associated with a single modeled storm at one static location. However, the design of a detention pond cannot truly model reality, as dynamic land use changes increase surrounding impervious cover and stormwater runoff volume. Therefore engineers conservatively design the detention pond for large storm events, or risk flooding neighbors. Unfortunately, hazards are associated with ponds that are too large, creating maintenance problems that diminish the effectiveness of the management technique over time (Reese 2001).

Detention ponds are also designed to handle the rainfall from a single storm event that evenly distributes rainfall over the entire watershed. However, multiple storm events can happen within a small time period, and be unevenly distributed throughout the watershed. These differences between modeled and real storms cause complications with the detention releases. Engineers attempted to overcome this deficiency by creating stormwater master plans, which could use advanced technology to model storm events throughout the watershed and inform coordinated release schedules of all the detention ponds.

Unfortunately these master plans take a long time to create, are very expensive to implement, and were demanded only after citizens have been flooded. Once the plans were adopted, the short-term memory of the community reduces the impotence to spend the required money enacting the plan. These shortcomings are indicative of the fact that detention ponds only aim to mitigate the cumulative effects of development on stormwater at centralized locations instead of addressing the hydrologic issues at their source (Reese 2001).

Water Quality and BMPs

In 1987, amendments to the Clean Water Act created a water quality component that established the National Permit Discharge Elimination System (NPDES). The NPDES requires that the Georgia Environmental Protection Division (EPD) track and regulate the amount of pollution that is introduced into all water bodies in the state, including Proctor Creek. The amount of pollution permitted to be discharged into a water body is based on the Total Maximum Daily Load (TMDL), which is the amount pollutants that can be accommodated in the water body without negatively disrupting the natural ecology (EPA Office of Water 2011).

When the health of the natural ecology is considered, a wide variety of pollutants become significant in the discussion of stormwater management, including total suspended solids, fecal coliform, temperature, dissolved oxygen, and heavy metals. This array of water quality metrics transferred the focus of stormwater management techniques from peak flow reduction to stormwater runoff volume reduction, which correlates to a reduction in all forms of pollution that negatively impact the creek's ecology (Reese 2001).

Proctor Creek is currently listed as an impaired stream due to its exceedance of the TMDL in fecal coliform pollution. The sewer systems in the watershed, both MS4 and CSS, now have NPDES permits aimed to protect the water quality of Proctor Creek, however there are still an indiscernible number of non-point sources of pollution that contribute to the impairment of the creek. These water quality concerns have become so pervasive that Atlanta's Watershed Department, the Chattahoochee River Keeper, and the West Atlanta Watershed Alliance all have separate water quality monitoring programs to help identify the non-point sources of pollution in Proctor Creek (Atlanta Regional Commission 2011).

The rest of this literature review will examine whether quality is improved by reducing volume, identify best management practices (BMPs) that are ideal for reducing stormwater runoff volume in the Proctor Creek watershed, and ascertain strategies for implementing BMPs that reduce stormwater runoff volume.

Green Stormwater BMPs Analysis.

Evidence of volume reduction improving water quality

The history of development in the Proctor Creek watershed shows a widespread and distributed replacement of the natural drainage pattern with a piped engineered system that conveys water from impervious surfaces. This direct connection between the impervious surfaces and the sewer system have created a first flush effect, whereby frequent small rain events result in increased amounts of stormwater runoff. This runoff is highly polluted as it accumulates pollutants before it is discharged into tributaries of Proctor Creek at high velocities, resulting in channel erosion and sedimentation (Geosyntec Consultants & Wright Water Engineers 2011).

By reducing the number of first flush events associated with small storm events, a drastic improvement in water quality can be achieved through the following mechanisms: 1) pollution concentration is reduced because large storm events is dilute pollution in the runoff (Georgia Adopt-A-Stream 2009); 2) sedimentation and creek erosion only are limited to large storm events, which is the historic condition of the creek that the biota have adapted to (Walsh, Fletcher and Ladson 2005); 3) since water from small storms does not enter the combined sewer system, there is more effective capacity to store large storm events, thereby decreasing the likelihood that CSO events would occur on an average annual basis (Department of Public Works 2002).

Walsh et al, 2005 have proved that stormwater management solutions need to be at the same scale as the underlying detrimental sources. Since the major source of the first flush phenomena results from alterations of the natural drainage patterns, restoration efforts must also be targeted to the stormwater drainage patterns. These hydrologic source controls effectively reduce the number of first flush events their negative impact to creeks and their biota (Figure 3). The findings from these studies have motivated the recent research and promotion of small-scale widely distributed stormwater Best Management Practices (BMPs) around the country (Streckler, et al. 2004).

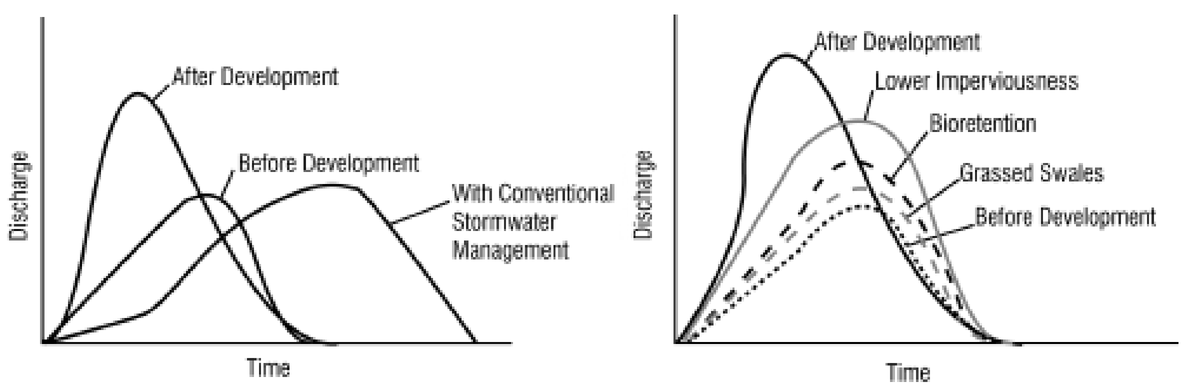


Figure 3: Effects of Stormwater BMPs on Hydrograph
chesco.org

Hydrological dynamics of stormwater BMPs

The total volume of runoff reduction associated with stormwater BMPs is a factor of two performance metrics that capture both the amount of the site the BMP treats and the stormwater BMP performance: *capture efficiency* * *volume reduction fraction*. Capture efficiency is the fraction of long-term runoff volume managed by a stormwater BMP for the site. Volume reduction is the fraction of the captured volume that is lost in the stormwater BMP and does not discharge to the surface water. The following discussion will expand upon the hydrological dynamics that contribute to the volume reduction fraction for each stormwater BMP, as the capture efficiency is unique to each site's dimensions and characteristics (Geosyntec Consultants & Wright Water Engineers 2011).

The volume reduction fraction for each stormwater BMP is dependent on the processes of infiltration, evaporation and evapotranspiration. Infiltration is the process by which surface water enters the soil, converting it to sub-surface and ground water. Evaporation occurs when the sun's energy is transferred to liquid water, thereby transforming it into a gaseous state that resides in the atmosphere. Evapotranspiration is the loss of water from the soil both by evaporation and by transpiration of plants during the photosynthesis process (Geosyntec Consultants & Wright Water Engineers 2011). Table 1 displays commonly used BMPs and the primary process by which the BMPs reduce stormwater runoff (EPA Office of Water 2005).

Table 1: Processes to Reduce Runoff Volume in BMPs

BMP Category	Type of BMP	Infiltration	Evaporation	Evapotranspiration
Infiltration mechanism	**Grass-lined detention basin**	**Y**	N	N
	Pervious/porous pavement	**Y**	N	N
Vegetated open channels	**Grass channels**	**Y**	N	N
	Grass swales	**Y**	**Y**	**Y**
Filtering practices	**Sand/organic filters**	**Y**	N	N
	Bioretention areas	**Y**	N	Y
Retention practices	**Dry retention ponds**	N	N	N
	Wet retention ponds	N	**Y**	N
	Constructed wetlands	N	**Y**	**Y**
Temporary storage	**Rain barrels/cisterns**	N	N	N

Which stormwater BMPs reduce the most volume

While the primary process' contributing to volume reduction is known, the actual volume reduction fraction still must be calculated by comparing the inflow of water volume vs. the outflow of water volume for each BMP type. This is a difficult analysis to perform because historical stormwater BMP implementations were targeted at improving water quality, with few data points on runoff volume inflows and outflows being recorded. To make sense of these impediments, Geosyntec Consultants and Wright Water Engineers (2011) selected studies from the International BMP Database that have comparable inflow and outflow volumes, then normalized and graphed the data to enable comparisons between BMPs based on volume reduction (Geosyntec Consultants & Wright Water Engineers 2011).

The BMP included in this study were organic filters (grass biofilters), grass swales, bioretention areas, dry infiltration basins, wet retention ponds, and wetlands (Appendix A). The results show the stormwater BMP types best suited to reduce the runoff volume from small storms events are vegetated stormwater BMPs: grass-lined infiltration basins, grass swales and bioretention areas. The worst performing stormwater BMP types where those that retain water, e.g. detention practices (Geosyntec Consultants & Wright Water Engineers 2011). With this information, it is possible to establish a "green" subgroup of stormwater BMPs, referred to in this paper as Green Stormwater Best Management Practices (GSwBMPs).

Unfortunately the permeable pavers BMP type did not have a robust enough set of comparable studies to be included in the Geosyntec and Wrightwater Engineers analysis. However, the study area contains large extents of impervious surface from roadways and parking lots in clustered locations. This prompted further research for analysis of this stormwater BMP type. Multiple studies demonstrated the effectiveness of pervious pavement in reducing runoff volume when used in place of other impervious road types (Fassman and Blackbourn 2010; Collins, Hunt and Hathaway 2008; Department of Watershed Management 2006).

With review of these studies, the following list of Green Stormwater BMPs have been delineated for potentially runoff reduction in the Proctor Creek watershed: grass-lined infiltration basins, grass swales, bioretention areas, and permeable pavers. To calculate the potential volume reduction fractions for these GSwBMPs, climate and site conditions for the watershed must first be described so that appropriate design guidelines can be prescribed.

Proctor Creek Climate

The Proctor Creek watershed is located in a humid subtropical climate and receives an average of 50 inches of rainfall per year (NOAA National Weather Service 2014). Rainfall is delivered in a variety of storm events, which are classified by the likelihood that they will occur within a given year, i.e. lower percentage storms more likely to occur. The predominate storm events accounted for in stormwater regulations are the 85, 90, and 95% storm events for BMP design criteria, correlating to 0.8-, 1.0-, and 1.2-inched of rainfall over a 24-hour period respectively (Clary and Leisenring 2012). This standardization is heavily influenced by the federal government's self-imposed stormwater runoff requirements, whereby all federal development projects must account for the stormwater runoff generated from a 90% rainfall event (EPA Office of Water 2009). Therefore, analysis conducted in this paper will also require GSwBMPs to reduce the runoff from a 90% storm event, i.e. 1-inch of rainfall over a 24-hour period. Also, all volume reduction fractions established will be derived for this storm event.

Volume reduction fractions are also dependent on the site characteristics of land cover, size of catchment, soils, and depth to groundwater. While land cover and the size of catchment will vary based on every site, the soil composition and depth to groundwater are relatively consistent throughout the Proctor Creek watershed. The average groundwater depth for the watershed is 52 ft, making groundwater table depth an insignificant factor in GWsBMP placement (US Geological Survey 2014). Conversely, the majority of the soils composition in the watershed are classified as Hydrologic Soil Groups C or D, meaning all the soils are a mixture of silt, sand or loam with clay (US Geological Survey

2014). The fine particulate size of the clay reduces the infiltration rate to 0.0-.15 in/hr, thus necessitating soil amendments for any GSwBMPs heavily dependent on infiltration (Natural Resources Conservation Service 2007).

Design Guidelines

a) *Grass swales*

Overview: Grassed swales are broad shallow channels that use vegetation to filter, retain and reduce stormwater runoff. The primary process by which grass-lined detention basins reduce runoff volume is through infiltration, accompanied by slight reductions from evapotranspiration (EPA Office of Water 2005). This GSwBMP type has large amounts of excess storage capacity, and can drain sites of 1-5 acre(s). When compared to other GSwBMP types, grassed swales takes up a relatively small amount of space to reduce volume. They are meant to be implemented as pretreatment for other GSwBMPs or in lieu of rip-rap swales and curb and gutters. Grassed swales are able to be implemented on all soil types (Perrin, Milburn and Szpir 2009).

Design: Grass swales are designed to have a wide bottom channel width (2-8 ft.) with slight slopes in the channel and steeper slopes for the channel sides (3:1-5:1). The channel should have 12-24 inches of rock aggregate under a permeable soil mixture. An overflow pipe needs to be placed at the outflow location, and designed so as not to cause erosion. To increase stormwater runoff reduction, the overflow pipe should be placed at a height that allows the water to flood inside the swale, but not overflow it. Dams in the channel may be used to slow the water and increase infiltration, while planting deep rooted grasses can encourage evapotranspiration (Department of Watershed Management 2006) (Appendix B). Grass swales must be maintained to ensure erosion is not occurring within the channel. Installing dams and mowing the vegetation in the channel reduces erosion by reducing the water flow velocity (EPA Office of Water 2005).

Volume Reduction Fraction: If this GSwBMP is properly designed, implemented, and maintained, the volume reduction fraction for a 1-inch 24-hour storm event is .65 (Geosyntec Consultants & Wright Water Engineers 2011).

b) Grass-lined detention basins

Overview: Grass-lined detention basins are shallow excavated ditches that have been backfilled with amended soils and stone, then covered with grass. The primary process by which grass-lined detention basins reduce stormwater runoff volume is infiltration, accompanied by slight reductions from evapotranspiration (EPA Office of Water 2005). Grass-lined detention basins have large amounts of excess storage capacity, and can drain sites of 5-10 acres. When compared to other BMP types, grass-lined detention basins take up a relatively small amount of space to reduce volume. They are meant to be implemented for individual sites or multi-site runoff treatment. Since grass-lined detention basins rely on infiltration, sandy clay loam are the only soils where this GSwBMP is effective (Perrin, Milburn and Szpir 2009).

Design: Grass-lined detention basins are designed to have a flat basin floor covered with grass turf, and berms along the sides. Soils with low infiltration rates should be amended with sands and rock to allow for water storage and lingering infiltration. An overflow structure needs to be placed at the outflow location, and designed so as not to cause erosion (Department of Watershed Management 2006) (Appendix C). Stormwater volume reduction can be improved by ripping the compacted subsoils to increase infiltration capacity, and planting deep rooted grasses to encourage evapotranspiration from the basin (Tyner, Wright and Dobbs 2009). Surface clogging can quickly reduce the effectiveness of these systems, therefore sedimentation is the principal maintenance concern. Grass-lined detention basins should be built once the soils have stabilized, i.e. after construction, and pretreatment controls, e.g. grass swales, should be used to reduce unwanted sedimentation (EPA Office of Water 2005).

Volume Reduction Fraction: If this GSwBMP is properly designed, implemented, and maintained, the volume reduction fraction for a 1-inch 24-hour storm event is .43 (Geosyntec Consultants & Wright Water Engineers 2011).

c) *Bioretention cells*

Overview: Bioretention cells are excavated trenches which are then back filled with engineered soils, covered with a layer of mulch and planted with a mixture of grasses, shrubs and trees. The primary processes by which bioretention cells reduce stormwater runoff volume is through infiltration and evapotranspiration (EPA Office of Water 2005). Bioretention cells do not have large amounts of excess capacity and can only drain sites of ¼ - 1 acre. When compared to other GSwBMP types, bioretention cells take up a large amount of space to reduce volume. Bioretention cells are meant to be implemented as treatment for roadways and parking lots, and are able to be implemented on all soil types (Perrin, Milburn and Szpir 2009).

Design: Bioretention cells are designed to be excavated areas that are backfilled with an engineered soil mix where a vegetative mix of trees, shrubs and grasses are planted. Since the subsoils have limited infiltration rates, an underdrain that connects to the MS4 needs to be placed in the engineered soil layer, which is composed of 85-88% sand, 8-12% clay/silt and 3-5% organic matter. Use an upturn in the overflow pipe to increase ponding and expand capacity, and install a forebay to spread the inflow and reduce erosion (Appendix C). Regular pruning encourages plant growth and increases evapotranspiration processes (Perrin, Milburn and Szpir 2009). Surface clogging can reduce the effectiveness of these systems. These GSwBMPs should be built once the soils have stabilized, i.e. after construction, and pretreatment controls, e.g. grass swales, should be used to reduce unwanted sedimentation in larger bioretention cells (EPA Office of Water 2005). Seasonal mulching, pruning and plant replacement are necessary to maintain a healthy vegetative mix in these GSwBMPs.

Volume Reduction Fraction: If this GSwBMP is properly designed, implemented, and maintained, the volume reduction fraction for a 1-inch 24-hour storm event is .74 (Geosyntec Consultants & Wright Water Engineers 2011).

d) Pervious Pavement

Overview: Pervious pavement is similar in strength to traditional pavement, but is designed to not use fine aggregate in the pavement mix, permitting porous openings to remain in the pavement. These pores allow water to percolate through the pavement, where it is stored in a gravel base. The primary process by which pervious pavement installations reduce stormwater runoff is through infiltration, accompanied by slight reductions from evapotranspiration (EPA Office of Water 2005). Pervious pavement installations are only meant to be implemented in place of other imperious surfaces, e.g. parking lots. When compared to other GSwBMP types, pervious pavement installations take up the largest amount of space to reduce volume. Since this GSwBMP is reliant on infiltration, sandy clay loam are the only soils where pervious pavement installations are effective (Perrin, Milburn and Szpir 2009).

Design: Pervious pavement installations are designed to have pervious pavement placed on top of a layer of fine aggregate, followed by a reservoir layer of stone and filter fabric separating the stone from the base-soils. Since the soils have limited infiltration rates, an underdrain that connects to the MS4 needs to be installed in the reservoir layer (Perrin, Milburn and Szpir 2009). Use an upturn in the overflow pipe and enlarge the reservoir layer to increase ponding and expand capacity (Appendix E). Small rock aggregate should be placed in the top stone layer to increase capillary size and encourage evapotranspiration (Tyner, Wright and Dobbs 2009), while pervious concrete should be chosen as the pavement material, due to the larger pore sizes and concrete's integrity during hot summer months (Perrin, Milburn and Szpir 2009). Surface clogging quickly reduces the effectiveness of this GSwBMP. Therefore pervious pavement installations should not be placed under trees (Fassman and Blackbourn

2010), nor near active construction sites with unstable soils (Collins, Hunt and Hathaway 2008). If clogging occurs use street vacuums to clear the pores.

Volume Reduction Fraction: If this BMP is properly designed, implemented, and maintained, then volume reduction fraction for a 1-inch 24-hour storm event is .36 (Collins, Hunt and Hathaway 2008).

Table 2: Design Criteria for Green Stormwater BMPs

GSwBMP Type	Watershed Size	In-Situ Soils	Water Table Depth	Volume Reduction
Bioretention	¼ acre – 1 acre	All	>2' from bottom of cell	.74
Pervious Pavement	¼ acre - 5 acres	Sandy clay loam	>2' from bottom of pavement cut	.36
Grassed Swales	1 acre – 5 acres	All	Any	.65
Infiltration Basins	1 acre	Sandy clay loam	>2' from bottom of cell	.43

Implementation Strategies for BMPs

Overview

There are three strategies a municipality can use to assign responsibility for externalities associated with stormwater runoff: enforce stormwater BMP implementation through regulatory ordinances, fine development for runoff while providing credits to encourage stormwater BMPs installation, and putting in stormwater BMPs in the municipal right of way (Campbell and Corley 2012). The three programs that will be used as models for these implementation strategies are Atlanta's Post-Development Stormwater Ordinance, Washington D.C.'s Stormwater Retention Credit Trading Program, and Philadelphia's CSO Remediation and Regulatory Control.

Post-Development Stormwater Ordinance: Atlanta

Atlanta's Post-Development Stormwater Ordinance is the most straightforward of the implementation strategies. This ordinance was passed in the City of Atlanta's codes in 2013, with the stated purpose "to preserve and/or restore natural hydrologic conditions on development sites" (City of Atlanta 2013).

The performance criteria for this ordinance is fixed: “the stormwater runoff volume generated by the first 1.0 inch of rainfall shall be retained on-site.” This retention of rainfall is to be accomplished through the use of GSwBMPs, however traditional detention methods may be used is undue hardships are demonstrated by the developer (City of Atlanta 2013).

The extent to which this performance criteria is applied to a site is dependent on both the type of land disturbance that is occurring, and whether the land use for the site is residential or commercial. For residential land uses, i.e. single family, any new development or total redevelopment of the site must have the performance criteria apply to the entire site. If the land disturbance on the residential land use is for partial redevelopment that increases the impervious cover by 1,000 sq feet, then the performance criteria is applied only to the newly built impervious area. For commercial land uses, i.e. non-single family, any new development of the site must have the performance criteria apply to the entire site. If the land disturbance on a commercial site is redevelopment of 35% or less of the site, then the performance criteria applies only to the newly built impervious area, otherwise the performance criteria applies to the entire site (City of Atlanta 2013).

This ordinance also establishes a series of meetings and protocols that must be followed to allow the development to be permitted. The first step in this process is to have a stormwater consultation meeting with the site development office. This consultation meeting is an opportunity for the permitting office to clearly define their stormwater expectations before the developer spends time and money drafting technical engineering documents. The studies required for this meeting are existing conditions, proposed site plans, infiltration rates, and a natural resource inventory (City of Atlanta 2013).

The developer then submits a Stormwater Management Plan, which details how the performance criteria for the stormwater management will be met. This plan is a package of the following technical documents stamped which are signed by a Practicing Engineer: analysis of the sites impact to the hydrology downstream, an erosion and sedimentation control plan, an operations and maintenance plan and an inspection agreement. This Stormwater Management Plan ensures that the land disturbance does not cause flooding, erosion, or sedimentation downstream and encourages maintenance considerations to be included in the design of the GSwBMPs (City of Atlanta 2013).

Stormwater Retention Credit Trading Program: Washington DC

While Washington DC also has a post-development stormwater ordinance, an adjustable performance criteria and the establishment of a stormwater credit trading program add more complexity compared to Atlanta's ordinance. The Stormwater Retention Credit Trading Program was established in 2013 with the stated purpose "to meet pollutant removal goals, reduce peak discharges, and pass extreme floods" (Center for Watershed Protection 2013).

The performance criteria for this ordinance differs from Atlanta's ordinance by requiring all land disturbance activities retain stormwater runoff based on calculations for the entire site. For all new development, the stormwater retention value (SWRv) is calculated as the runoff from a 1.2" rainfall event. If redevelopment occurs in a specially designated zone, then the SWRv is calculated as the runoff from a 1.0" rainfall event. For redevelopment outside this zone, the SWRv is calculated as the runoff from a 0.8" rainfall event.

While this ordinance's performance criteria can be more demanding than Atlanta's ordinance, property owners have more flexibility in the way in which they meet the performance criteria. Only 50% of the SwRV must be retained on-site, with the difference able to be made up through purchasing Stormwater Retention Credits (SRCs) from private land owners, paying an in-lieu fee (ILF) to the watershed department, or directly conveying the volume to a shared BMP with available retention capacity. For the SwRV that is kept on-site, the administrative procedures for GSwBMP implementation and build out are very similar to those procedures explained in Atlanta's ordinance. For the SwRV that is remaining, both a SRC and an ILF correspond to one gallon of SwRV for one year.

Stormwater Retention Credits are generated by using GSwBMPs to retain more SwRV than required by the ordinance, but does not exceed the runoff generated by a 1.7" rainfall event. SRCs can be generated by retrofitting existing sites, or by building more capacity than required on development sites. The SRCs can be developed and owned by someone other than the land owner and are only viable during the agreed upon maintenance period. SRCs may be certified for up to three years, and the credits generated in those three years may be banked, retired without being used, or traded at any time within the certified time period, e.g. can sell all credits at the very beginning. In order to facilitate trade of SRCs, the government of Washington D.C. created a market that publicly displays the purchasing and selling prices of SRCs. SRCs are not required to be purchased/sold within the same subwatershed as the land disturbance. If the SRC has already been sold, the seller is still responsible for all associated maintenance, and will be charged 110% of an ILF by the watershed department if maintenance is not upheld (Center for Watershed Protection 2013).

CSO Remediation and Regulatory Control: Philadelphia

Philadelphia's implementation strategy for green infrastructure is the result of a Consent Decree that was agreed to by both the EPA and the City of Philadelphia in 2011 to reduce the total number of combined sewer overflows (CSOs) into the Delaware River. Under direction from the Consent Decree, the City of Philadelphia's Water Department created a CSO Long Term Control Plan called Green City, Clean Waters. As the Green City, Clean Waters Plan is a document that is used to satisfy legal requirements, it's purpose is more technical than the previously described strategies "[to] eliminate the mass of pollutants that would otherwise be removed by the capture of 85% by volume of the combined sewage collected in the Combined Sewer System (CSS) during precipitation events on a system-wide annual average basis" (The Philadelphia Water Department 2011).

The Watershed Department aims to meet the stated purpose by implementing green stormwater BMPs to reduce the volume introduced to the combined sewer system. The performance criteria used to measure the reduction in volume is called a "Greened Acre"; which is measured by the area of impervious cover (in acres) multiplied by the depth of water over the impervious cover (1.0- 1.5 inches) retained by green stormwater BMPs (Equation 1).

Equation 1: Greened Acres Calculation

$$GA = IC * Wd$$

GA = Greened Acres
IC = impervious cover utilizing GSI (acres).
Wd = the depth of water over the impervious surface that can be physically stored in the facility (inches).

Decision points are established every 5 years, whereby progress towards the intermediate and final water quality standards will be analyzed, resulting in Evaluation and Adaptive Plans. These plans will use the following metrics to measure the success of the Greened Acres performance criteria: number of GSwBMP projects contributing to Greened Acres; volume of stormwater managed by new infrastructure other than GSwBMPs; and the total volume percent capture for the combined sewer system.

To meet the purpose of the Green City, Clean Waters Plan, the Watershed Department has established the goal of "convert[ing] more than 1/3 of the impervious cover within the sections of the City served by combined sewers to Greened Acres" (The Philadelphia Water Department 2011). To accomplish this within the 25 year allotted time period, the Water Department must be responsible for building and managing much of the green stormwater infrastructure. The Watershed Department created a Green Stormwater Infrastructure Planning Group create initiatives that prioritize GSwBMP projects. These initiatives include stormwater management enhancement districts, a green parking lots initiative, a vacant land initiative, and better coordination with the Public Works Department.

Stormwater management enhancement districts are areas where there is a high potential for the use of interconnected GSwBMPs. Once these areas are identified, consultants are hired to create a Stormwater Improvement Plan that coordinates with stakeholders, current planning initiatives, and long term development interests. The green parking lots initiative uses economic incentives and zoning codes to encourage depaving and retrofits that use GSwBMPs to manage runoff associated with parking lots. The vacant land initiative aims to find vacant parcels that can be bought by the Watershed Department and retrofitted to use GSwBMPs to retain runoff from surrounding areas. A suitability analysis is performed in order to prioritize large, publicly owned parcels that are close to stormwater inlets and have low slopes, a large surrounding drainage area, and an absence of buildings or historical dumping. Finally, the GSI Planning Group coordinates with the Public Works Department in order to ensure that wherever possible, impervious infrastructure constructed by Public Works will be coupled with green stormwater BMPs built by either the Water Department or Public Works. The most common impervious infrastructure targeted are sidewalks and streets, with focus on implement the green stormwater BMPs: bioretention pits, curb cuts to grass swales and porous pavement.

Summary Table of Policy-Based Implementation Strategies

Table 3: Summary of Implementation Strategies

Implementation Strategy	Volume of Runoff Treated	Achievement Criteria
Post-Development Stormwater Ordinance	First 1.0” of rainfall from impervious surfaces on private parcels	All runoff generated must be treated onsite by GSwBMPS

Stormwater Retention Credit Trading Program	First 1.2” of rainfall from entire site on private parcels	Half of runoff generated must be treated onsite by GSwBMPS, other half of runoff generated can be treated offsite by purchasing stormwater retention credits
CSO Remediation and Regulatory Control	1.0” of rainfall from 1/3 of public impervious surfaces in Combined Sewer Drainage Area	All runoff generated must be treated by GSwBMPS on public property

Literature Review Conclusion

In conclusion, this literature review began with an in depth analysis of how the historical land patterns and their associated stormwater management have led to the environmental issues in the Proctor Creek watershed. The hydrologic dynamics of the current green stormwater best management practices (BMPs) were then explained to demonstrate how stormwater runoff volume reductions improve water quality. Those stormwater BMPs that best reduce volume in the Proctor Creek watershed were defined, and design characteristics were prescribed to accurately estimate volume reduction fractions. Lastly, a document review analyzed state of the art policies, programs and plans currently used to implement stormwater BMPs around the country.

While the explanations of stormwater issues and latest attempts to mitigate these issues is very helpful to planners and policy makers, it is unclear how these policy based implementation strategies would impact water quality on a watershed scale. Since it takes a large amount of time and effort to gain momentum for large-scale policy reforms such as these, it is necessary to have scenario-based models that reasonably estimate stormwater runoff reductions and the associated water quality improvements. The results from these scenarios can then be compared, and policy recommendations can be gleaned from such an exercise. Therefore, the next steps in this paper are to design and run such a model.

Methodology

Overview

To examine the amount of stormwater runoff reduction achieved with the policy-based GSwBMP Implementation Strategies, different scenarios will be created that model similar but structurally different plausible futures based upon the alternative policy options. The scenarios will be derived using a GSwBMP suitability analysis, GSwBMP volume reduction fractions, and logic gleaned from the unique implementation strategies. ESRI's ArcGIS software will be used to calculate the stormwater runoff rates from parcel boundaries, land covers, and rainfall data, while an extension developed by the EPA will be used to estimate GSwBMP placements based on design criteria already reviewed.

Suitability Analysis

A suitability analysis will be performed to find locations in the Proctor Creek watershed appropriate for GSwBMP implementation. These locations have no relation to any particular policy option, and will remain constant throughout all scenarios developed. The EPA's SUSTAIN model will be used for this analysis, as it includes a relevant pre-processing procedure for BMP placement developed by stormwater engineers, and can therefore be employed in other studies that duplicate these methodologies. The preprocessing tool also has interactive windows that can tailor the suitability analysis to the GWsBMP design criteria established in the literature review.

SUSTAIN's suitability analysis is run on the ArcGIS software package, and requires the spatial analyst extension for raster dataset manipulation. Raster datasets define space as an array of equally sized cells arranged in rows and columns. Each cell contains an attribute value and location coordinates, and groups of cells that share the same attribute value represent the same type of feature (ESRI 2015). The suitability analysis overlays multiple GIS data layers representing significant factors for siting GSwBMPs.

All of the layers have cells in the same geographic location, but the cells contain different attribute values dependent on what information is captured in the layer (Figure 4).

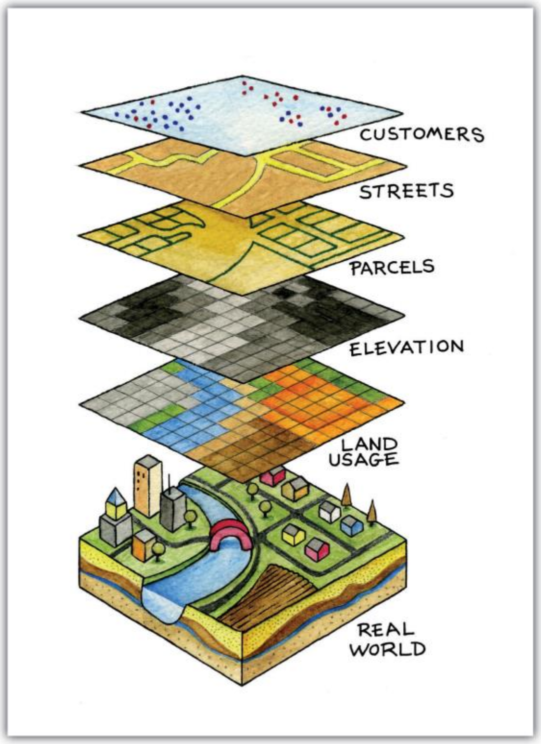


Figure 4: Raster Dataset Visualization
http://support.esri.com

The suitability analysis applies a pre-defined weighting scheme to the different attribute values for each cell, then sums the values to locate the most suitable areas for the desired placement, such that the highest values correlate to the most suitable locations. The interactive Data Management window for assigning raster layers that are used as inputs for the SUSTAIN suitability analysis is displayed in Figure 5, and the justification for the inclusion of each layer is listed in Table 4

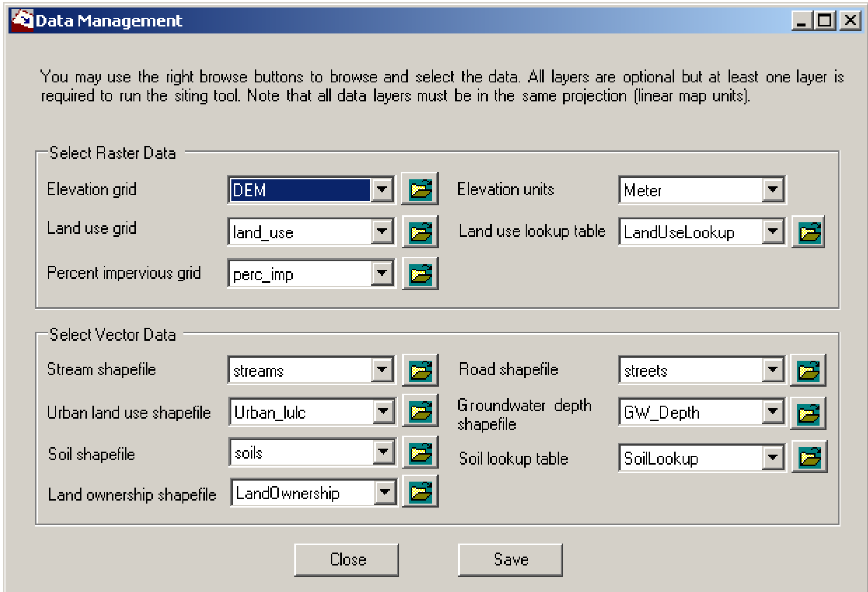


Figure 5: SUSTAIN's Data Management Interface

Table 4: Suitability Analysis Raster Dataset Requirements

Raster Layer	**Reason Important to Suitability Analysis**
DEM	calculate the drainage slope and drainage area
Land Use	used to eliminate unsuitable areas for BMPs
Percent Imperviousness	used to identify areas of high BMP need
Hydrologic Soil Group	used to eliminate areas where infiltration in not an option
Urban Land Use	locates impervious surfaces generating runoff (buildings, parking, and streets)
Roads	places certain BMPs types that must be within a specific road buffer area
Streams	places certain BMP types outside a buffer to minimize the impact on streams
Groundwater Table Depth	if the groundwater is too shallow; infiltration BMPs will not work properly

Once the inputs for the suitability analysis have been delineated, specific BMPs that to be placed in the watershed are chosen according to user preferences. Each of the selected BMP types have their own citing criteria specific to design requirements, which can be tailored to the GWsBMP design criteria established in the Literature Review (Table 2). These design criteria are used within the SUSTAIN framework by altering the weights for inputs, e.g. flatter slopes have higher values, or not allowing certain raster values to be valid, e.g. only sandy or sandy clay loam soils valid (Figure 6).

Table 2: Design Criteria for Green Stormwater BMPs

GSwBMP Type	Watershed Size	In-Situ Soils	Water Table Depth
Bioretention	¼ acre – 1 acre	All	>2' from bottom of cell
Pervious Pavement	¼ acre - 5 acres	Sandy clay loam	>2' from bottom of pavement cut
Grassed Swales	1 acre – 5 acres	All	Any
Infiltration Basins	1 acre	Sandy clay loam	>2' from bottom of cell

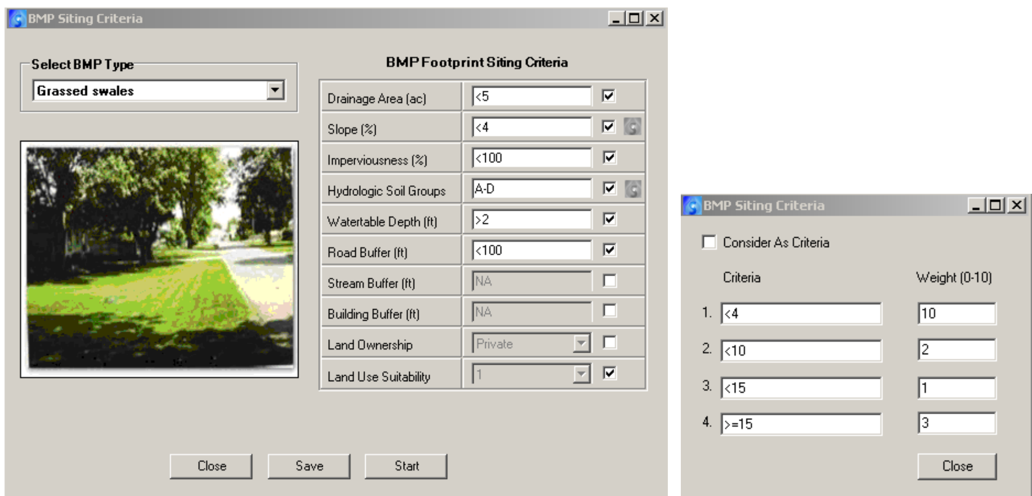


Figure 6: SUSTAIN's BMP Siting Criteria

Once the criteria has been set for each of the four selected GSwBMP types, the suitability analysis is executed. The output contains separate vector shapefiles that represent suitable locations for each GSwBMP type, and is then used as an input for the scenarios to be developed.

Scenario Development

Overview

The following discussion is focused on how to build the scenarios, which are based upon the policy-based implementation strategies discussed in the literature review. The framework for creating these scenarios analyzes the amount of regulated stormwater runoff generated from the impervious surfaces, overlays this regulated stormwater runoff to the entity responsible through parcel boundaries, and places GSwBMPs in feasible locations based upon the suitability analysis in order to model the amount of stormwater volume reduction feasible.

Due to the fact that they are the legal definition of land ownership, parcel boundaries will be used to identify responsibility for stormwater runoff generated from impervious surfaces and delineate the catchments for feasible GSwBMPs. The Fulton County Tax Assessor's Office generates and distributes a Fulton County parcels shapefile complete with land use information, site conditions, and property values. This shapefile was clipped to the Proctor Creek watershed boundary, and a manual inspection of parcels was performed to eliminate slivers of polygons that had been removed in the clipping process.

Because the parcel records were derived from the assessor's tax information, many of the records had overlapping geometries with different TAXPINs (for example, condos and multifamily housing units are taxed individually while occupying the same parcel boundary). The parcels were cleaned using the "Delete Identical" tool to delete all records with the same geometry. This is necessary as multiple records with identical geometries would over-represent the amount of spatial area in the parcel boundaries, corresponding to increased runoff generated. A "type" field was then added to the shapefile's attribute table, and was used to determine public and private property based on the parcel's land use types.

The impervious surfaces shapefile was assembled from buildings, parking lots, and curb-to-curb streets shapefiles that were obtained from the City of Atlanta's online data repository. Two fields were added to the attribute table for the impervious surfaces shapefile: the first contained information about the type of impervious cover, while the second contained the acreage of the impervious surfaces, which was determined using the Calculate Geometry tool. The acreage of these impervious surfaces was used to find the amount of stormwater runoff generated through the use of the Rational Method of

Stormwater Runoff Calculation (Equation 2) (AMEC Earth and Environmental 2001). Within this equation, all impervious surfaces are treated the same, and have a runoff coefficient of .95.

$$Q_{imp} = C_{imp} * i * A_{imp}$$
$$Q_{imp}\ is\ the\ runoff\ rate\ in\ cubic\ feet\ per\ second,$$
$$C_{imp}\ is\ the\ runoff\ coefficient,$$
$$i\ is\ the\ hourly\ rainfall\ intensity,$$
$$A_{imp}\ is\ the\ impervious\ area\ in\ acres.$$

Equation 2: Impervious Surfaces Stormwater Runoff Calculation

As discussed in the literature review, the amount of stormwater runoff volume reduced by each GSwBMP type is calculated by multiplying the stormwater reduction fraction by the runoff generated in the catchment area for the GSwBMP. Due to the legal responsibility of the developer to reduce runoff from their site, the parcel boundaries serve as the catchment area for the GSwBMPs. The Rational Method of Stormwater Runoff Calculation will also be used to calculate the amount of stormwater runoff generated from the parcels. However, all impervious surfaces have a runoff coefficient of .95, while all non-impervious areas will be treated as pervious areas, and have a runoff coefficient of .35 (Equation 3) (AMEC Earth and Environmental 2001).

$$Q_{parcel} = \left(C_{imp} * i * A_{imp}\right) + (C_{non-imp} * i * A_{non-imp})$$
$$Q\ is\ the\ runoff\ rate\ in\ cubic\ feet\ per\ second,$$
$$C\ is\ the\ runoff\ coefficient,$$
$$i\ is\ the\ hourly\ rainfall\ intensity,$$
$$A\ is\ the\ impervious\ area\ in\ acres.$$

Equation 3: Parcels Stormwater Runoff Calculation

The volume reduction fraction assigned to each parcel is dependent on output from the SUSTAIN suitability analysis. Parcels were identified as being suitable for each type of BMP by adding a field to the attribute table for every BMP type. This is accomplished by using the Select by Location tool to find any parcel that was intersected by the BMP suitability output generated from the SUSTAIN model. If the parcel was suitable for a specific type of BMP, then the field was filled in with a “1” value, and if not, the field remained as a “<Null>” value. The volume reduction fraction was then assigned to each parcel based on what type of BMP was suitable for the parcel, if multiple BMPs were able to be implemented on the parcel, the BMP with the highest volume reduction fraction was chosen for implementation (Table 5).

Table 5: GSwBMP Reduction Fractions

GSwBMP Type	Volume Reduction
Bioretention	.74
Pervious Pavement	.36
Grassed Swales	.65
Infiltration Basins	.43

The final amount of stormwater runoff reduced from the GSwBMP is calculated as the amount of runoff generated from the parcel multiplied by the runoff reduction fraction (Equation 4) (Geosyntec Consultants & Wright Water Engineers 2011).

$$Q_{BMP} = Q_{parcel} * (RF_{BMP}) \quad (4)$$

Q_{BMP} *is the runoff reduced from GSwBMP*,
Q_{parcel} *is the runoff from the parcel, i.e. catchment*,
RF_{BMP} *is reduction fraction for the BMP type*.

Equation 4: GSwBMP Runoff Reduction Calculation

With the framework for the scenarios completed, logic based upon the different policy-based implementation strategies can be used to build the individual scenarios. For reference, a summary of the policies is provided in Table 3. The next section will use the reasoning inherent in each implementation strategy, and will adjust performance criteria based upon the current state of stormwater regulations in the City of Atlanta to allow better comparisons between the different scenarios.

Table 3: Summary of Implementation Strategies

Strategy	Volume of Runoff Treated	Achievement Criteria
Post-Development Stormwater Ordinance	First 1.0” of rainfall from impervious surfaces on private parcels	All runoff generated must be treated onsite by GSwBMPS
Stormwater Retention Credit Trading Program	First 1.2” of rainfall from entire site on private parcels	Half of runoff generated must be treated onsite by GSwBMPS, other half of runoff generated can be treated offsite by purchasing stormwater retention credits
CSO Remediation and Regulatory Control	1.0” of rainfall from 1/3 of public impervious surfaces in Combined Sewer Drainage Area	All runoff generated must be treated by GSwBMPS on public property

Post Development Stormwater Ordinance

In the Post-Development Stormwater Ordinance, all privately held parcels are required to reduce the runoff generated from the first 1.0” of rainfall onsite through GSwBMPs. To accomplish this, impervious surfaces must be matched to the respective parcel. This was achieved by using the Identity tool to overlay parcel boundaries onto the impervious areas, and imprinting the impervious areas with the attributes of the overlapping parcels. The field that was previously used for impervious surface acreage was recalculated using Calculate Geometry tool. The impervious area was summarized based on the parcel TAXPIN, resulting in a table that contained all of the impervious acreage per parcel. A join was then used to attach the impervious surface acreage to the parcel feature class. Finally, a code was used to replace impervious acreage <Null> values with 0, so that future runoff derivations would not be distorted due to the way <Null> values are used in calculations in ArcMap.

The volume produced by 1.0” of rainfall on impervious surfaces and volume reduced by each parcel’s BMP were then calculated in new fields using the Rational Method discussed in the Scenario Overview section. This step is straightforward because the parcel record in the attribute table contained impervious acreage, catchment runoff, and GSwBMP reduction fraction.

Since the developer is only responsible for reducing the amount of runoff generated for the first 1.0" of runoff from impervious surfaces, the final step for this scenario is to select the minimum value between the runoff generated by impervious surfaces and the runoff reduced by the GSwBMP per parcel. All excess runoff reductions generated by the BMPs will not be of use to the developer, and any excess runoff generated by the impervious surfaces will need to be treated through detention BMPs permissible through the hardship clause in the Post Development Stormwater Ordinance.

Stormwater Credit Trading Program

In the Stormwater Credit Trading Program, half of runoff generated by the first 1.0" of rainfall on impervious surfaces on private parcels must be treated onsite by GSwBMPs, while the other half can be treated offsite by purchasing stormwater retention credits. The main driver for purchasing stormwater retention credits is the property values for the proposed development. If property values are high, then there is more incentive to purchase retention credits, if the property is a low-valued, vacant property, there is incentive for mitigation specialists to purchase the property for retention credit generation. These assumptions are based off the original logic for implementing the Stormwater Credit Trading Program in Washington D.C **Invalid source specified.**.

To model these incentivized behaviors, the property values were normalized by acreage to enable comparisons and mimic actions taken by property owners. These values were normalized by adding a field, and dividing the property values in the tax assessor's data by the acreage of the parcel. One assumption here is that the ten percent of the parcels with the highest property values per acre would opt to purchase stormwater credits instead of retaining all stormwater on-site (the top 10% of parcels are those which are valued over $325,000). The demand for stormwater credits is to be met by mitigation experts that can purchase low-valued, vacant properties to use for stormwater retention credit generation. These properties were identified by using the Select by Attributes tool to select parcels with vacant land use codes and that have a land value per acre less than $20,000. Once the parcels that will demand and generate stormwater retention credits were identified, modeling the runoff rates could be begin.

The same process for assigning responsibility for runoff generated by impervious surfaces was used in this scenario as in the Post-Development Stormwater Ordinance scenario. The parcel boundaries were overlaid onto the impervious areas, the impervious surface acreage was recalculated, and the impervious acreage was summarized and joined to the parcel based on the TAXPIN.

Next, the volume produced by 1.0” of rainfall on impervious surfaces and volume reduced by each parcel’s BMP were calculated in new fields using the Rational Method discussed in the Scenario Overview section. However, unlike the Post-Development Stormwater Ordinance scenario, only 50% of this stormwater generated from impervious surfaces is required to be treated onsite. This was calculated for the high valued parcels in a new field using Equation 5.

$$Q_{credits\ bought} = Q_{reg} - (.5 * Q_{reg})$$

Equation 5: Credits Demanded in Stormwater Retention Credit Trading Scenario

A second field was added to calculate the number retention credits built based on the number of GSwBMP installations on the low-valued, vacant parcels. Since the retention credits can be generated for rainfall events up to 1.7”, the amount of parcel runoff was calculated with for this rainfall event from the Rational Method reviewed in the overview section. Because these parcels already have runoff reduction requirements, the excess amount of runoff reduced from 1.7” rainfall event was subtracted from runoff reduced from a 1.0” rainfall event (Equation 6).

$$Q_{credits\ generated} = Q_{generated} - Q_{reg}$$

Equation 6: Credits Generated in Stormwater Retention Credit Trading Scenario

The final step in this model is to find out how much overall stormwater would be reduced when using the Stormwater Retention Credit Trading Program (Equation 7).

$$Q_{final} = Q_{regulated} - Q_{credits\ bought} + Q_{credits\ generated}$$

Equation 7: Runoff Reduced by GSwBMPs in Stormwater Retention Credit Trading Scenario

CSO Remediation and Regulatory Control

The CSO Remediation and Regulatory Control scenario targets reduction of stormwater runoff generated from pubic impervious cover within the combined sewer drainage basin. Atlanta's combined sewer drainage basin within the Proctor Creek watershed was delineated by examining records within the Long-Term CSO Plan developed for Atlanta during the Consent Decree in the early 2000's (Department of Public Works 2002). The main goal of this scenario is to see whether it is feasible to reduce the amount of runoff from publicly owned impervious surfaces by 1/3, and if so how much reduction in stormwater runoff would occur.

To begin modeling this scenario, the total amount of publicly owned impervious area in the Combined Sewer Area needs to be determined. The first step was to use the Clip tool to reduce the impervious feature class to only features within the Combined Sewer boundary. Since the impervious feature class already had a field that delineated the type of impervious feature—e.g., building, street, or parking—the Select by Attributes tool was used to select all impervious features that were in the public right of way, i.e. streets. This selection was then expanded upon using the Select by Location tool to add to the selection any buildings that intersected or were placed on public parcels. The total imperviousness on public land was exported to a new feature class, manually inspected for buildings and parking lots that share borders with public parcels but are not located on top of the public property, and the total impervious acreage was recalculated by using the Calculate Geometry tool.

After the impervious surface was calculated, the next step was to find out where BMPs could be sited. The criteria for placing BMPs on public parcels is the same as it has been in previous scenarios (i.e., the site is only limited by the SUSTAIN BMP suitability analysis), however the streets can only be paired with pervious concrete, as the utility of these streets would be ruined if they were converted to GSwBMPs. While this caveat would be important for future scenarios, it is not relevant to this scenario as the entire combined sewer drainage basin has soils that are not conducive to infiltration methods, and therefore there are no suitable areas for pervious pavement placement.

The total runoff from the public parcels was calculated by adding the runoff generated from impervious surfaces located on these parcels along with the runoff generated by non-impervious surfaces.

The total amount of impervious surface per parcel was calculated by using the Identity tool to imprint the impervious area with the parcel TAXPIN. The acreage for these impervious areas was then calculated using the Calculate Geometry tool. The impervious area acreage was summarized by the TAXPIN and joined with the parcels to match total impervious area with the parcel. The total runoff coming off the parcels was calculated using the following equation:

$$Q_{pub} = .95 * 1.0" * A_{imp\ acre} + \ .95 * 1.0" * A_{non-imp\ acre}$$

Equation 8: Runoff Generated by Public Land

A definition query was then used to remove all parcels where the impervious runoff was equal to the parcel runoff, as this indicated that the parcel was completely covered by an impervious surface, and could not have a BMP implemented on it without destroying the purpose of the parcel.

The total number of impervious surfaces for this calculation was determined by clipping the impervious surface feature class by the parcels. This was done because the public utilities can overlap onto multiple parcels when implementing BMPs. The runoff generated from the parcel was then multiplied by runoff reduction fraction for the BMP that was suitable for all parcels.

Because the City is only responsible for reducing the amount of runoff generated for the first 1.0” of runoff from impervious surfaces, the final step for this scenario is to select the minimum value between the runoff generated by impervious surfaces and the runoff reduced by BMP types. All excess generated by the BMPs will not be of use to the City, and any excess runoff generated by the impervious surfaces will need to be treated through existing sewer infrastructure

Summary Table of Scenarios Developed

Table 6: Summary of Scenarios Developed

Scenario	**Criteria Applies to:**	**Criteria:**
Post-Development Ordinance	Private Impervious cover	1.0” of all impervious cover runoff retained onsite in the entire watershed
Retention Credit Trading Program	Private Impervious cover	0.5” of impervious cover runoff retained onsite high value property; 1.0” of impervious cover runoff retained onsite in medium value properties; 1.7” of impervious cover runoff retained onsite on vacant, low value properties
BMPs in Municipal Right of Way	Public Impervious cover	1/3 of public impervious cover has 1.0” of runoff retained in the downtown core.

Results

BMP Suitability Analysis

SUSTAIN's BMP suitability analysis resulted in four shapefiles representing the suitable areas for each of the four GSwBMPs. The GSwBMP type with the largest amount of suitable area is bioretention cells with 1,679 acres, followed closely by grassed swales with 1,384 acres. These two GSwBMPs have very similar suitability areas, as their siting criteria are very similar, and the main limitation for grassed swales compared to biretention cells was the steepness of the slope (Figure 7). The GSwBMP type with the third most suitable area is infiltration basins with 103 acres, while the GSwBMP type with the least amount of suitable area is pervious pavement with only 12 acres. Both of these GSwBMPs are limited in their suitability extent due to their dependency on well-draining soils, and are therefore clustered in the north-west portion of the watershed where the soil types are candy clay loam (Figure 7).

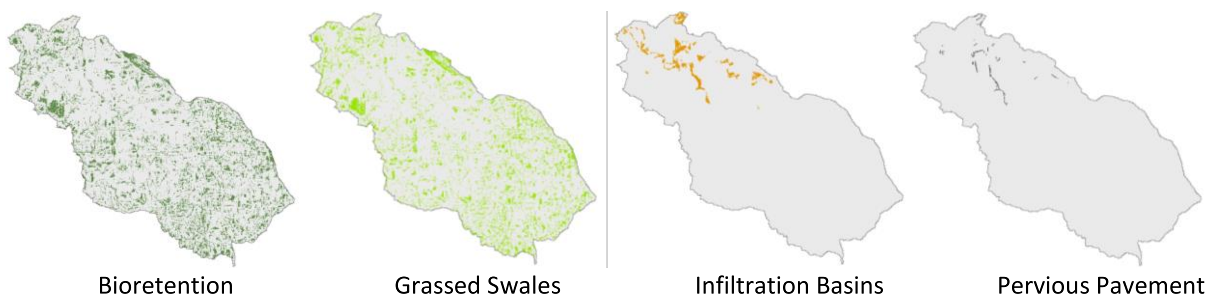
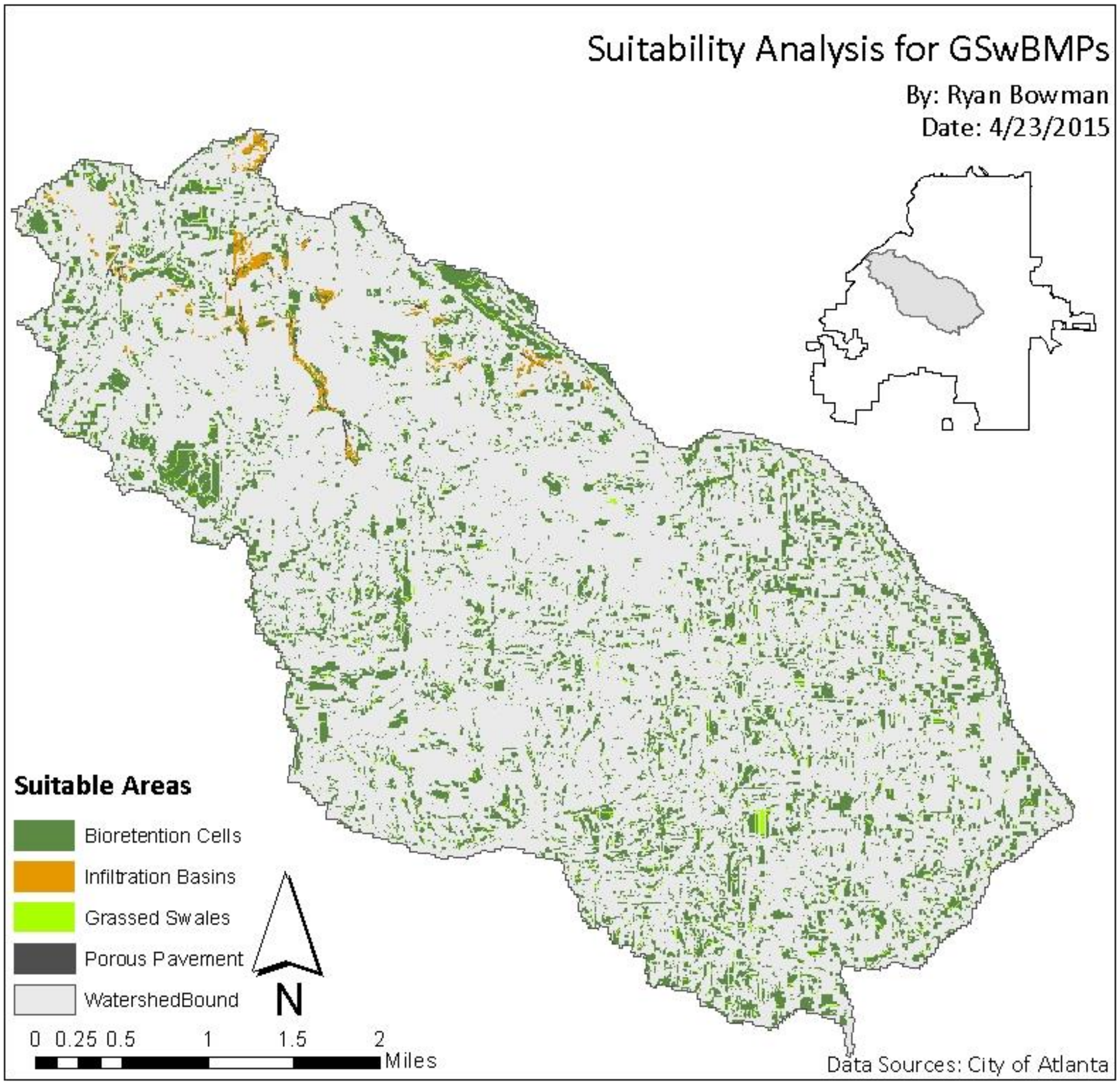


Figure 7: Suitability Analysis Output

As stated in the Scenario Development section, if GSwBMPs overlap, the GSwBMP with the highest volume reduction fraction will be chosen for implementation on the parcel. Map 1 displays this logic by layering the different SUSTAIN suitability analysis outputs to show GSwBMPs with the highest reduction fractions as the top-most visible layer.



Map 1: Suitability Analysis for GSwBMPs

Post-Development Stormwater Ordinance

The stormwater runoff required to be reduced on private parcels in the Post-Development Stormwater Ordinance Scenario is 1,460 cubic feet per sec (cf/sec), while the total amount of runoff reduced through GSwBMPs is 1,163 cf/sec. The remaining 297 cf/sec of stormwater runoff will need to apply for the hardship clause. This equates to 80% of the required stormwater reductions achieved through GSwBMPs and 20% treated with traditional stormwater management, i.e. detention BMPs. However, the total amount of stormwater that is feasibly reduced with GSwBMPs on private parcels is 1,926.63 cf/sec. Since there is no incentive to build GSwBMPs past the amount of regulated stormwater runoff for each individual parcel, 763 cf/sec of feasible runoff reductions using GSwBMPs are not realized (Chart 1).

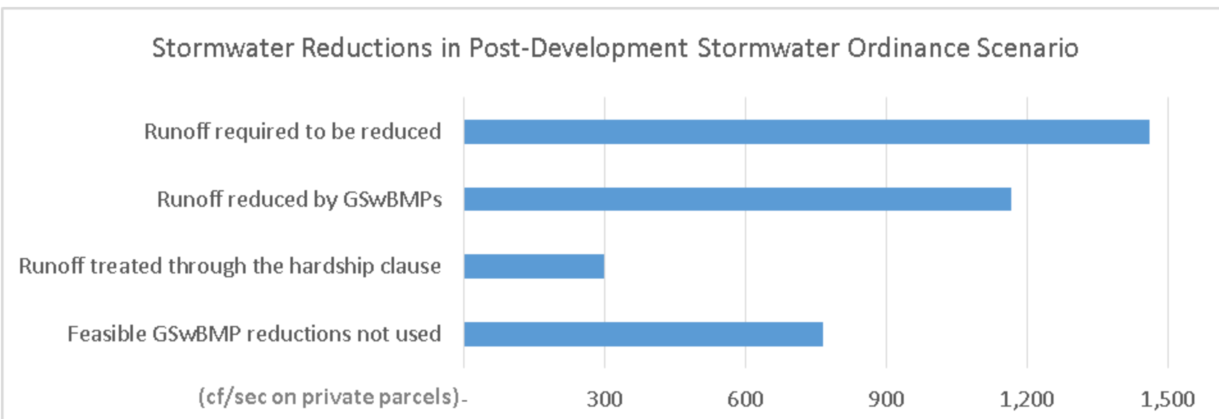
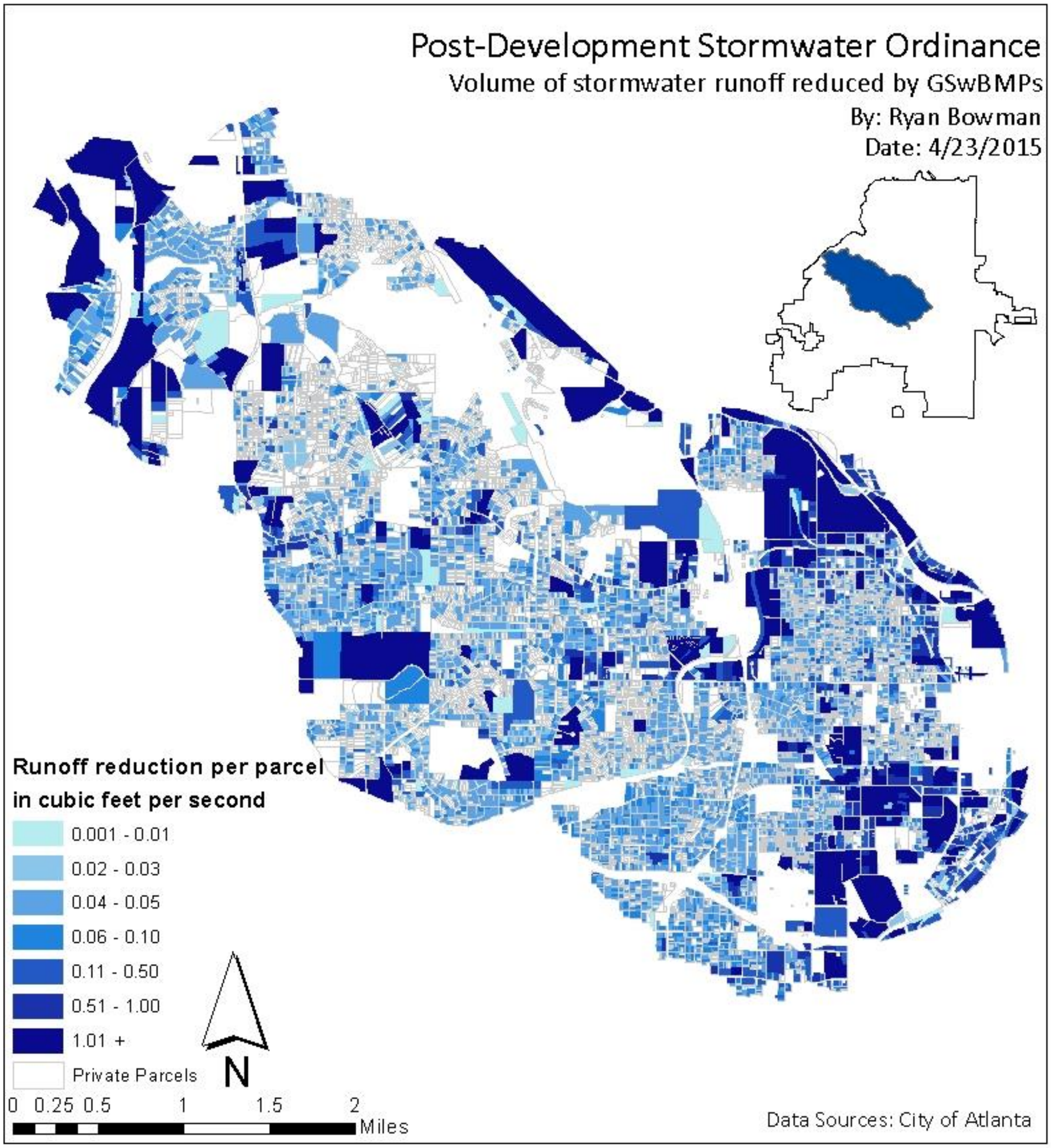


Chart 1: Stormwater Reductions in Post-Development Stormwater Ordinance Scenario

Of the 16,889 private parcels in the watershed, 14,090 have impervious surfaces that generate runoff onsite, while 9,459 have GSwBMPs reducing volume onsite. This leaves 4,631 parcels that are left to apply for the hardship clause, or about 67%, which are mainly concentrated on small, residential parcels (Map 2).



Map 2: Stormwater Reductions in Post-Development Stormwater Ordinance Scenario

Stormwater Credit Trading Program

The stormwater runoff required to be reduced on private parcels in the Stormwater Credit Trading Program Scenario is 1,460 cf/sec, while the total amount of runoff reduced through GSwBMPs is 1,065 cf/sec. The remaining 395 cf/sec of stormwater runoff will need to apply for the hardship clause. This equates to73% of the required stormwater reductions achieved through GSwBMPs and 27% treated with traditional stormwater management, i.e. detention BMPs. The total number of stormwater retention credits generated on low-valued, vacant private parcels is 123 cf/sec, while the total demand for these credits was 193 cf/sec (Chart 2).

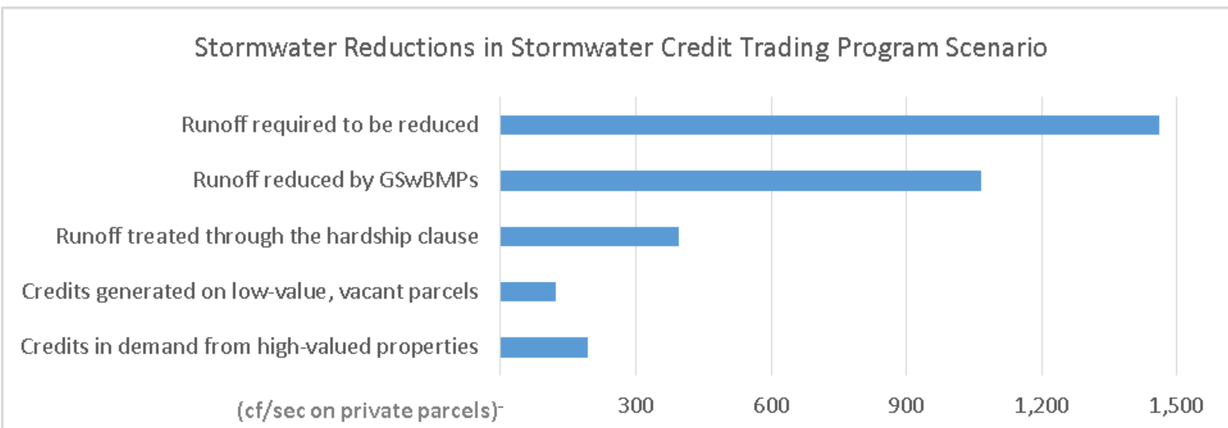
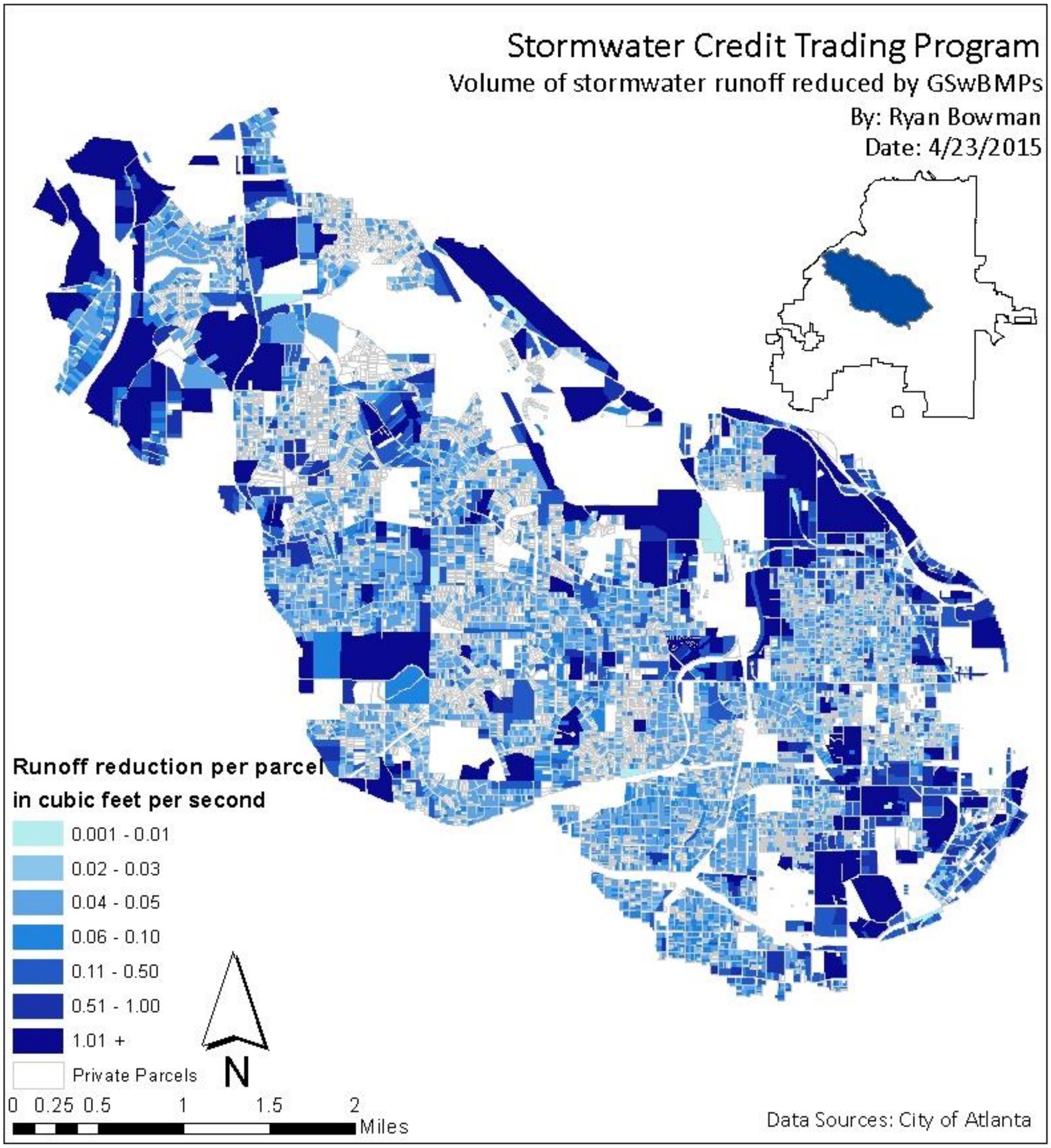


Chart 2: Stormwater Reductions in Stormwater Credit Trading Program

Of the 16,889 private parcels in the watershed, 14,090 have impervious surfaces that generate runoff onsite, while 10,640 have GSwBMPs reducing volume onsite. This leaves 3,450 parcels that are left to apply for the hardship clause, or about 76%, which are mainly concentrated on small, residential parcels (Map 3).



Map 3: Stormwater Reductions in Stormwater Credit Trading Program

CSO Remediation and Regulatory Control Plan

The stormwater runoff generated on public impervious surfaces is within the combined sewer drainage basin 432 cf/sec, while the stormwater runoff required to be reduced on public parcels in the CSO Remediation and Regulatory Control Scenario is through GSwBMPs is 154 cf/sec. The total feasible amount of runoff reduced through GSwBMPs on public parcels is 190 cf/sec, which is 123% of the stormwater runoff required to be reduced, and (Chart 1Chart 3).

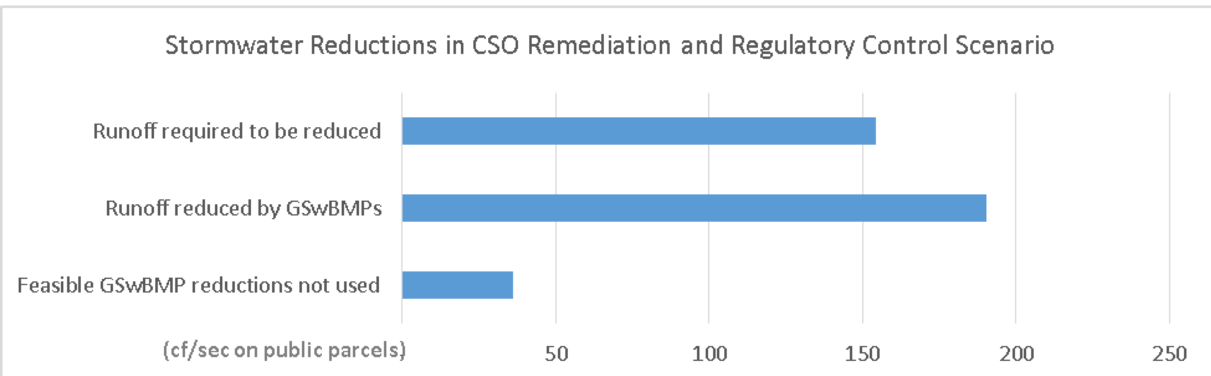
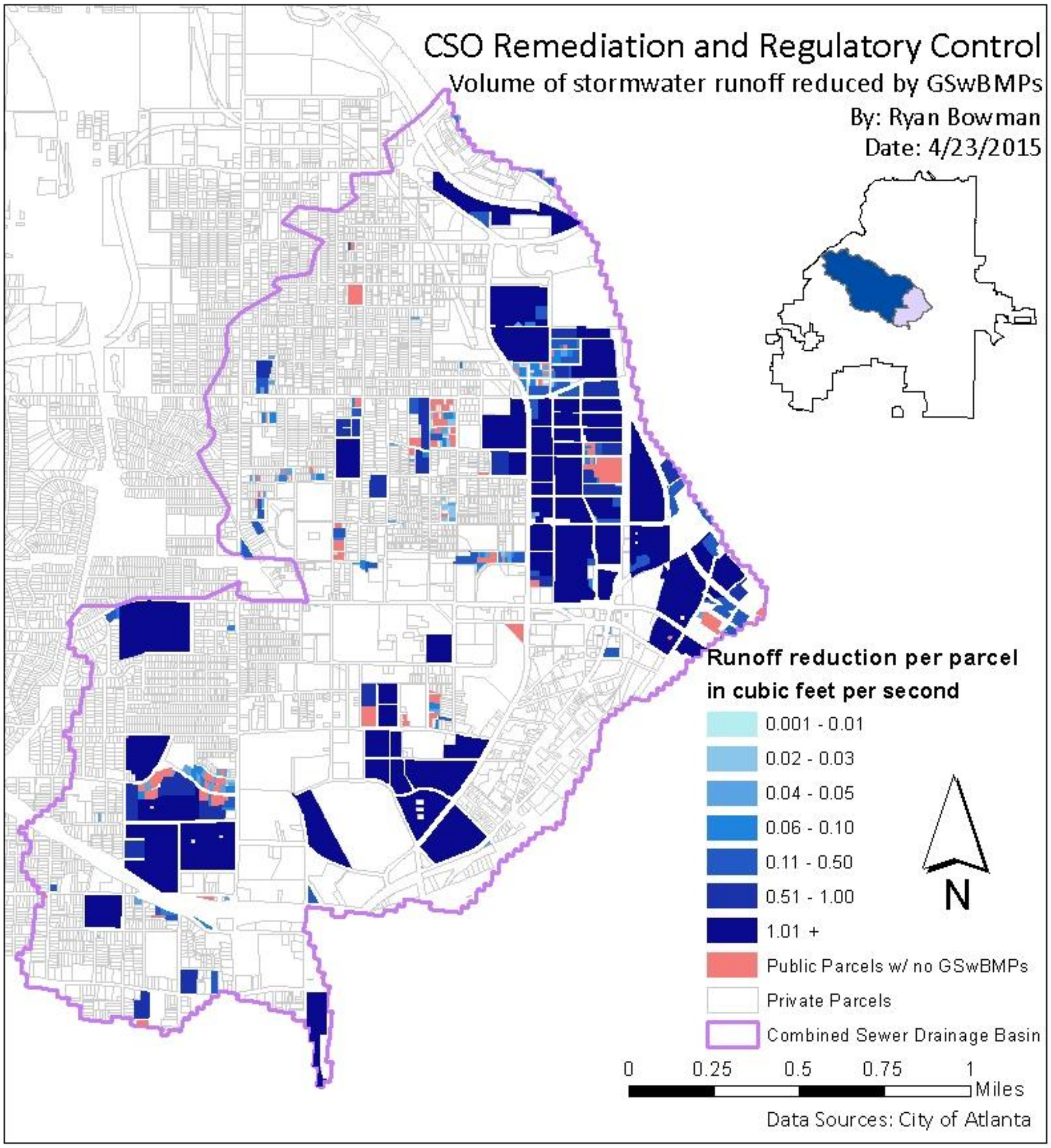


Chart 3: Stormwater Reductions in CSO Remediation and Regulatory Control Scenario

Of the 453 public parcels in the combined sewer drainage basin 212 are can feasibly place GSwBMPs to reduce volume onsite. The parcels that cannot reduce stormwater runoff with GSwBMPs onsite are predominately small parcels located in close proximity to other public parcels that are able to reduce stormwater runoff using GSwBMPs (Map 4).



Map 4: Stormwater Reductions in CSO Remediation and Regulatory Control Scenario

Discussion

Increase in runoff from impervious surfaces

The total amount of runoff generated from impervious surfaces in this watershed is 2,728 cf/sec. However, if this land were covered with natural vegetation, the total amount of runoff generated would be 1,005 cf/sec. Therefore, the impervious cover in the watershed adds an additional 1,723 cf/sec of runoff. Since the total amount of runoff in the watershed is 5,275, the added impervious surfaces account for an additional 33% of stormwater runoff. In the combined sewer drainage basin, the impervious surfaces contribute to a 37% increase in the stormwater runoff. This analysis shows increases in stormwater runoff from impervious surfaces are significant in the combined sewer drainage area and the entire watershed.

Post-Development Stormwater Ordinance v. Credit Trading Program

In both the Post-Development Stormwater Ordinance and the Credit Trading Program Scenarios the amount of runoff reduce with GSwBMPs was lower than the amount of runoff generated from impervious surfaces (Chart 4).

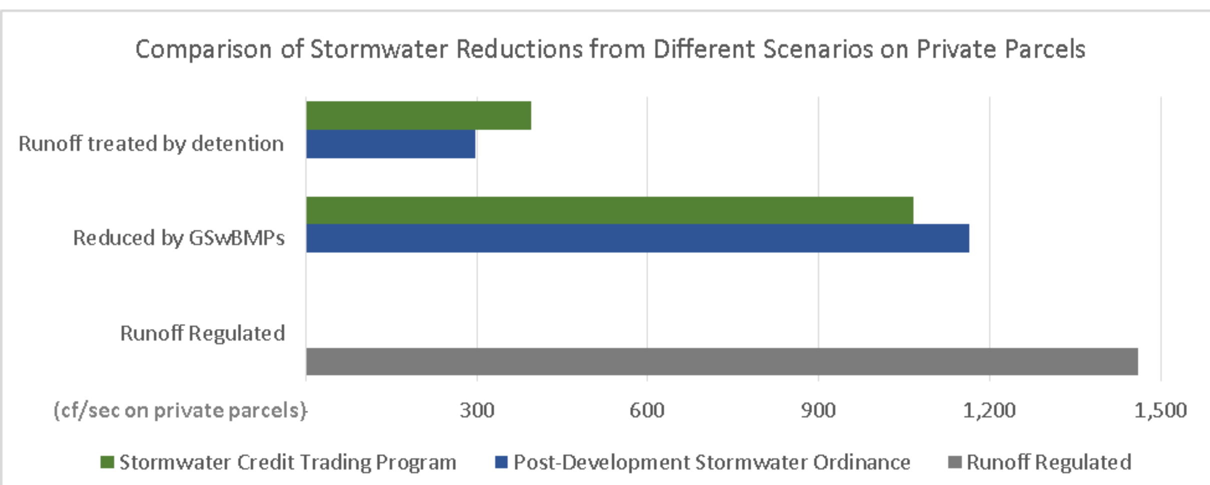


Chart 4: Comparison of Stormwater Reductions from Different Scenarios on Private Parcels

The Post-Development Stormwater Ordinance reduces 98 cf/sec more stormwater runoff through GSwBMPs, or 7% of the regulated stormwater runoff. However, the Credit Trading Program Scenario has 1,181 more parcels with GSwBMPs implemented onsite, which is a 12% increase from the Post-Development Stormwater Ordinance. The incongruity between the total number of parcels and the amount of stormwater runoff reduced is due to the amount of stormwater required to be reduced per parcel. In the Stormwater Credit Trading Program Scenario, the amount of runoff required to be reduced was half of the total stormwater runoff, and the owners of parcels with high land values would choose to purchase retention credits instead of reducing the total amount of stormwater onsite. Many of these high land value parcels have a large overall area, high levels of imperviousness, and are clustered in the upper regions of the watershed. This created a large demand for the stormwater retention credits.

However, many of the low-value, vacant parcels that were chosen to generate stormwater retention credits were predominantly smaller parcels in the residential neighborhoods, In addition to the small size of the parcels, the land cover on the credit-generating parcels already contains a low runoff coefficient, causing less water per acre to be generated on non-impervious surfaces. If less water is generated on the parcel where the GSwBMP is installed then less water is available to be reduced. These factors result in a large number of credit-generating parcels with low amounts of runoff reduced.

Finally, many of the parcels that are used to generate stormwater retention credits are located in the lowest elevations of the watershed, close to Proctor Creek and the Chattahoochee River. The location of these credit-generating parcels effectively disconnects the treatment of the runoff from the source of the runoff, i.e. impervious surfaces. This may cause complications similar to those experienced when using detention methods (Figure 8).

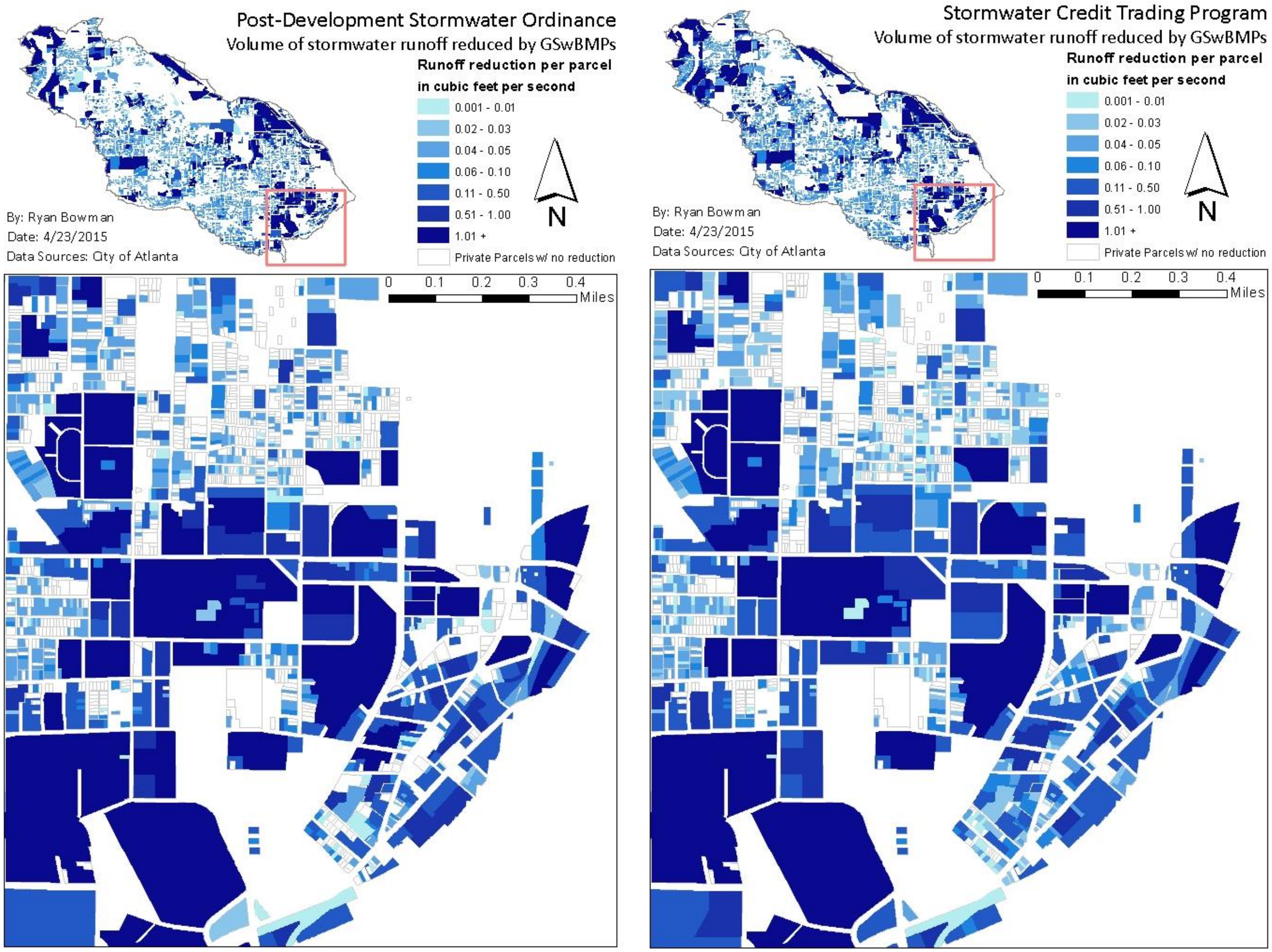


Figure 8: Comparison of Stormwater Reductions from Different Scenarios on Private Parcels

Implications of CSO Remediation and Regulatory Program Scenario

The total amount of stormwater runoff generated by impervious surface on private land in the combined sewer drainage area is 434 cf/sec, which is comparable to the 454 cf/sec of runoff generated by the stormwater on impervious surfaces on public land. However, when analyzing the amount of runoff reduce by each scenario in this area, the Post-Development Stormwater Ordinance Scenario reduced the most runoff at 348 cf/sec, while the Credit Trading Program Scenario reduced the second most at 267 cf/sec, and the CSO Remediation and Regulatory Control Scenario reduced the least at 212 cf/sec (Chart 5).

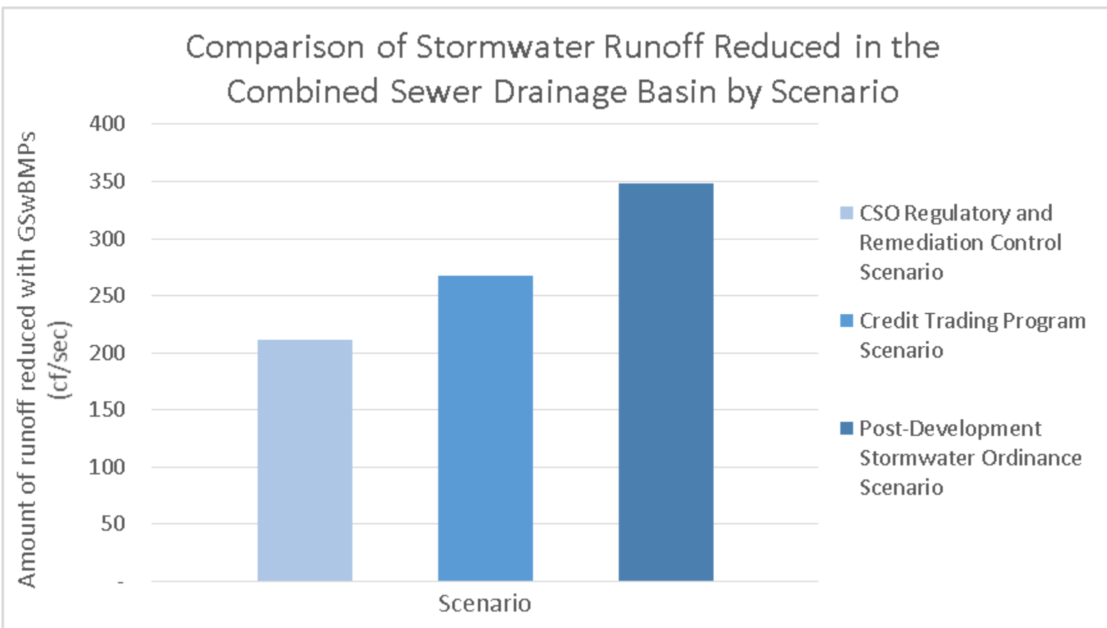


Chart 5: Comparison of Stormwater Runoff Reduced in the Combined Sewer Drainage Basin by Scenario

Conclusions

This study shows that impervious surfaces in the Proctor Creek watershed in Atlanta, Ga generate an added 1,723 cubic feet per second stormwater runoff, relating to 33% increase. On a watershed wide basis, private parcels contribute to a majority of this increased runoff, while in the combined sewer drainage basin the amount of runoff generated by public parcels is close to even with the amount of runoff generated by private parcels.

The EPA's SUSTAIN suitability analysis demonstrated that GSwBMPs are able to be implemented throughout the watershed, and the GSwBMP type with the largest amount of suitable area was bioretention cells. The BMP literature review showed that of all GSwBMP types, bioretention cells are able to reduce the most stormwater runoff per acre, which is primarily driven through the processes of evaporation and evapotranspiration. This analysis also showed that pervious pavement is difficult to achieve in this watershed due to low infiltration rates of poor draining soils.

The scenarios developed modeled were able to model the logic of the policy-based implementation strategies of the Post-Development Stormwater Ordinance, Stormwater Credit Trading Program, and CSO Remediation and Regulatory Control. The Post-Development Stormwater Ordinance scenario was the most effective implementation strategy, and was able to reduce 80% of the runoff generated from impervious surfaces on private parcels with GSwBMPs. The Stormwater Credit Trading Program would only reduce 73% of the runoff generated from impervious surfaces, while creating a spatial disconnect between the source of the increased runoff and the reduction of the runoff. The CSO Remediation and Regulatory Control scenario demonstrated that it is feasible to reduce over one third of stormwater runoff from impervious surfaces on public property through GSwBMPs.

Therefore, the Post-Development Stormwater Ordinance should continue, while the publicly owned parcels should be retrofitted to reduce runoff rates within the combined sewer drainage basin.

Limitations

As in modelling any scenarios, there are limitations to this study. The soil shapefiles that were used for SUSTAIN's BMP suitability analysis are created by the USGS through satellite imagery. While not be feasible for the entire watershed, the suitability analysis would be greatly improved upon by delineating statistically significant field inspection locations.

To more accurately model the runoff rates, runoff coefficients for each land cover could be applied on a parcel by parcel basis. The runoff rates could be further improved by including rainfall interceptance from tree canopy cover, and reducing runoff due to disconnected impervious cover.

When factoring the amount of runoff reduced through GSwBMPs, the catchment areas for said BMPs are dependent upon legal boundaries, whereas the actual catchments are dependent on slope as well as parcel boundaries. While this is take into consideration on the overall SUSTAIN BMP suitability analysis, it is not taken into consideration on the parcel level. Within the CSO Remediation and Regulatory Control scenario, many of the public parcels in the combine sewer drainage basin contained large building footprints that may limit the size of the GSwBMP installed.

Bibliography

About Proctor Creek. 2014. *The creek at a glance.* Accessed November 17, 2014. http://aboutproctorcreek.info/at-a-glance/.

AMEC Earth and Environmental. 2001. *Georgia Stormwater Management Manual Volume 2.* Atlanta, Ga: Atlanta Regional Commission.

Atlanta Journal Constitution. 2011. *Atlanta settles suit with residents over sewer, flood damage.* March 8. Accessed November 17, 2014. http://www.ajc.com/news/news/local/atlanta-settles-suit-with-residents-over-sewer-flo/nQrLC/.

Atlanta Regional Commission. 2011. *Proctor Creek - headwaters to Chattahoochee River watershed improvement plan.* Atlanta, GA: Atlanta Regional Commission.

Campbell, H.E., and E.A. Corley. 2012. *Urban Environmental Policy Analysis.* Armonk, NY: M.E. Sharpe, Inc.

Center for Watershed Protection. 2013. *Stormwater Management Guidebook.* Ellicott City, MD: District Department of the Environment.

City of Atlanta. 2013. "Atlanta Code of Ordinances: Post-Development Stormwater Management Ordinance." Atlanta, GA: City of Atlanta.

—. 2012. *Community investigation leads to DWM action.* June 2. Accessed November 17, 2014. http://www.atlantawatershed.org/newsroom/press-releases/community-investigation-leads-to-dwm-action/.

City of Atlanta, Department of Watershed Management. 2014. *The Proctor Creek watershed.* http://www.atlantawatershed.org/inside-dwm/offices/watershed-protection/atlantas-watersheds/the-proctor-creek-watershed/.

Clary, J., and M Leisenring. 2012. *International stormwater best management practices (BMP) Database: Narative overview of BMP database study characteristics.* Denver, CO: Wright Water Engineers, Inc & Geosyntec Consultants.

2013. *Code of Ordinances. Chap. 74, art. X.* Atlanta, GA: City of Atlanta .

Collins, K., W. F. Hunt, and J. M Hathaway. 2008. "Hydrologic comparison of four types of permeable pavement and standard asphalt in eastern North Carolina." *Journals of Hydrological Engineering* 13(12): 1146-1157.

Creative Loafing. 2001. *Here's where the poop in the Hooch comes from.* Accessed November 17, 2014. http://clatl.com/atlanta/heres-where-the-poop-in-the-hooch-comes-from/Content?oid=1233725.

Department of Public Works. 2002. *City of Atlant CSO remedial measures plan.* Atlanta, GA: City of Atlanta.

Department of Watershed Management. 2006. *Pennsylvania stormwater BMP manual.* Manual, Harrisburg, PA: Pennsylvania Department of Environmental Protection.

EPA Office of Water. 2011. *Clean Water Act § 122.26: storm water discharges.* Washington, D.C.: EPA Office of Water.

EPA Office of Water. 1994. *Combined sewer overflow (CSO) control policy; notice.* Washington, D.C.: Environmental Protection Agency.

—. 2008. *Fecal Coliform and E. coli.* 1 9. Accessed October 10, 2014. http://water.epa.gov/drink/contaminants/basicinformation/ecoli.cfm.

—. 2005. *National management measures to conrol nonpoint source pollution from urban areas.* Washington D.C.: Environmental Protection Agency.

—. 2014. *Sediments.* February 06. http://water.epa.gov/polwaste/sediments/.

EPA Office of Water. 1994. *Storm water discharges (applicable to State NPDES programs, § 123.25).* Washington, D.C.: Environmental Protection Agency: Water Division.

EPA Office of Water. 2009. *Technical guidance on implementing the stormwater runoff requirements for federal projects under Section 438 of the Energy Independence and Security Act.* Washington D.C.: US Environmental Protection Agency.

EPA Office of Water. 2007. *Total maximum daily loads with stormwater sources: A summary of 17 TMDLs. Report, EPA 841-R-07-002.* Washington, D.C.: Watershed Branch (4503T), Office of Wetlands Oceans and Watersheds.

EPA Urban Waters. 2013. *Urban Federal Waters Partnership.* Fact Sheet, Washington DC: Environmental Protection Agency.

EPA: Region 4. 2012. *The Urban Federal Waters Partnership: Partners for progress in Proctor Creek.* Atlanta, GA: EPA Region 4.

ESRI. 2015. *GIS Dictionary.* Accessed March 20, 2015. http://support.esri.com/en/knowledgebase/GISDictionary/term/raster.

Fassman, E., and S. Blackbourn. 2010. "Urban runoff mitigation be a permeable pavement system over impermeable soils." *Journal of Hydrologic Engineering* 475-485.

Georgia Adopt-A-Stream. 2009. *Biological & Chemical Stream Monitoring.* Atlanta, GA: Department of Natural Resources: Environmental Protection Division.

Geosyntec Consultants & Wright Water Engineers. 2011. *Technical Summary: Volume Reduction.* Denver, CO: International Stormwater Best Management Practices (BMP) Database.

Gomez-Ullate, E., J. R. Bayon, D. Castro, and S. J. Coupe. 2008. "Influence of geotextile on water retention in pervious pavements." *Proc., 11th Int. Conf. on Urban Drainage.*

Lai, F., T. Dai, J. Zhen, J. Riverson, K. Alvi, and L. Shoemaker. 2006. *SUSTAIN - An EPA BMP process and placement tool for urban watersheds.* Edison, NJ: U.S. Environmental Protection Agency, Office of Research and Development, Urban Water Management Branch.

Mitchell, Ceasar C. 2010. "Atlanta's water, Atlanta's future." *Clean Water Atlanta.* http://www.cleanwateratlanta.org/materials/.

Natural Resources Conservation Service. 2007. *Hydrology national engineering handbook: hydrologic soil groups.* Washington D.C.: U.S. Department of Agriculture.

NOAA National Weather Service. 2014. *Rainfall Scorecard.* Accessed November 28, 2014. http://www.srh.noaa.gov/ffc/?n=rainfall_scorecard.

Park Pride. 2010. *Proctor-North Avenue conceptual visioning plan.* Atlanta, GA: Park Pride.

Perrin, C, L. Milburn, and L Szpir. 2009. *Low Impact Development: A guidebook for North Carolina.* Guidebook, Raleigh: North Carolina State University.

Proctor Creek Stewardship Council. 2014. *A Grassroots, comprehensive appoach to improving our environment.* Accessed November 17, 2014. http://www.proctorcreek.org/.

Reese, Andy. 2001. "Stormwater paradigms." *Stormwater journal.* July. http://www.stormh2o.com/SW/Articles/Stormwater_Paradigms_218.aspx.

Shoemaker, L., J Riverson, K Alvi, J. Zhen, and R Murphy. 2011. *Report on enhanced framework (SUSTAIN) and field applications for placement of BMPs in urban watersheds.* Cincinnati, OH: National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency.

Stoner, N., C. Kloss, and C. Calarusse. 2011. *Rooftops to rivers: green strategies for controlling stormwater and combined sewer overflows.* New York, NY: Natural Resources Defense Council.

Streckler, E., M Quigley, B. Urbonas, and J. Jones. 2004. "Analysis of the expanded EPA/ASCE Internation BMP Database and potential implications for BMP design." *World Water and Environmental Resources Congress.* Salt Lake City, UT: American Society of Civil Engineers. 1-10.

The Conservation Fund. 2014. *Parks with purpose: Atlanta.* http://www.conservationfund.org/projects/proctor-north-avenue-community-revitalization/.

The Philadelphia Water Department. 2011. *Green City, Clean Waters: implementation and adaptive management plan.* Philadelphia, PA: The Commonwealth of Pennsylvania: Department of Environmental Protection.

The Wasington Times. 2014. *Waste still seeps into pollution-plagued creek.* January 23. Accessed November 17, 2014. http://www.washingtontimes.com/news/2014/jan/23/waste-still-seeps-into-pollution-plagued-creek/?page=all.

Trust for Public Land. 2014. *Proctor Creek Greenway.* Accessed November 20, 2014. https://www.tpl.org/our-work/parks-for-people/proctor-creek-greenway.

Tyner, J. S., W. C. Wright, and P. A. Dobbs. 2009. "Increasing exfiltration from pervious concrete and temperature monitoring." *Environmental Management* 90(8): 2636–2641.

U.S. Code. 1972. *33 U.S.C. § 1313.* Washington D.C.

US Geological Survey. 2014. *Groundwater levels for the nation.* Accessed November 20, 2014. http://nwis.waterdata.usgs.gov/usa/nwis/gwlevels.

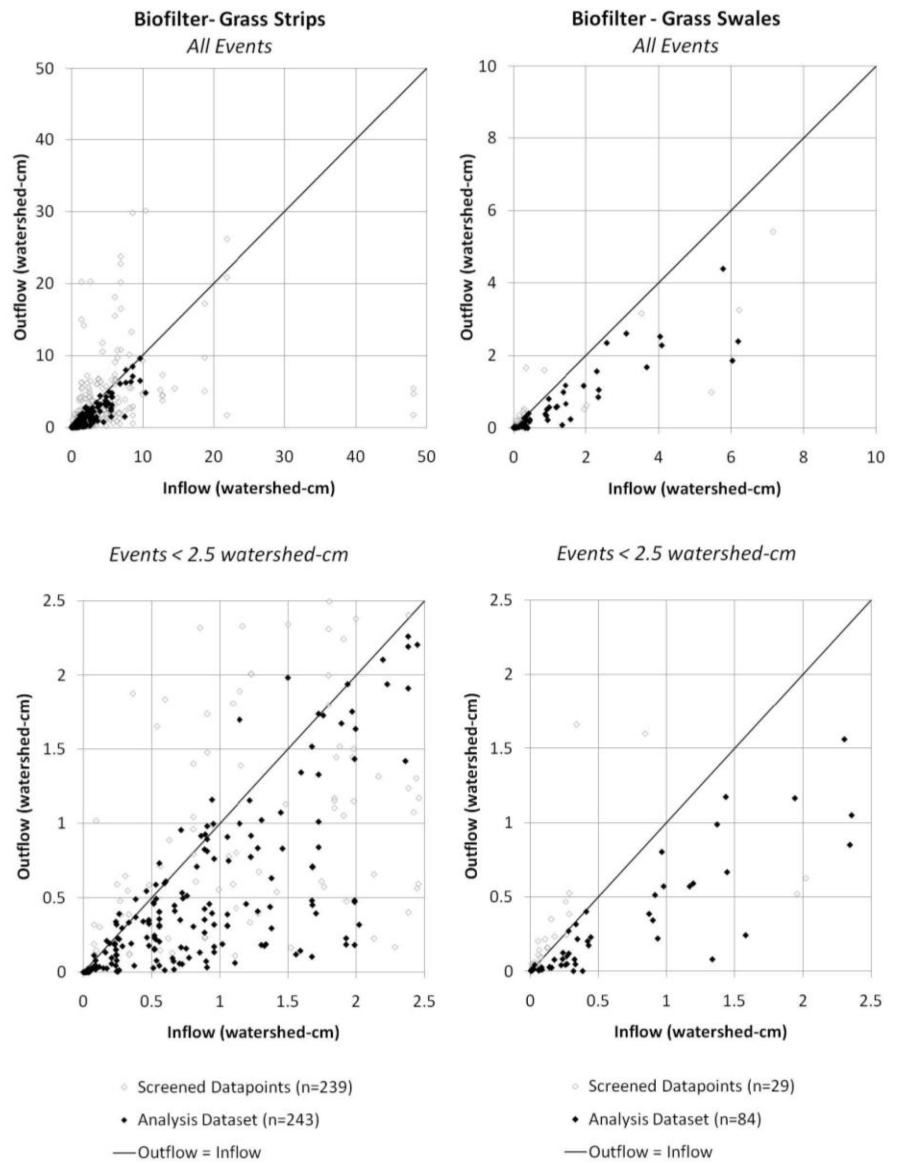
Walsh, C., T. Fletcher, and A Ladson. 2005. "Stream restoration in urban catchments through redesigning stormwater ecosystem: looking to the catchment to save the stream." *The North American Benthological Society* 24(3): 690-705.

Wheatley, Thomas. 2014. "Proposal to transform vacant Vine City lots into ambitious 16-acre park gets greenlight from Atlanta City Council committee." *Creative Loafing.* July 12. Accessed November 20, 2014. http://clatl.com/freshloaf/archives/2012/07/12/proposal-to-transform-vacant-vine-city-lots-into-ambitious-16-acre-park-gets-greenlight-from-atlanta-city-council-committee.

Appendices

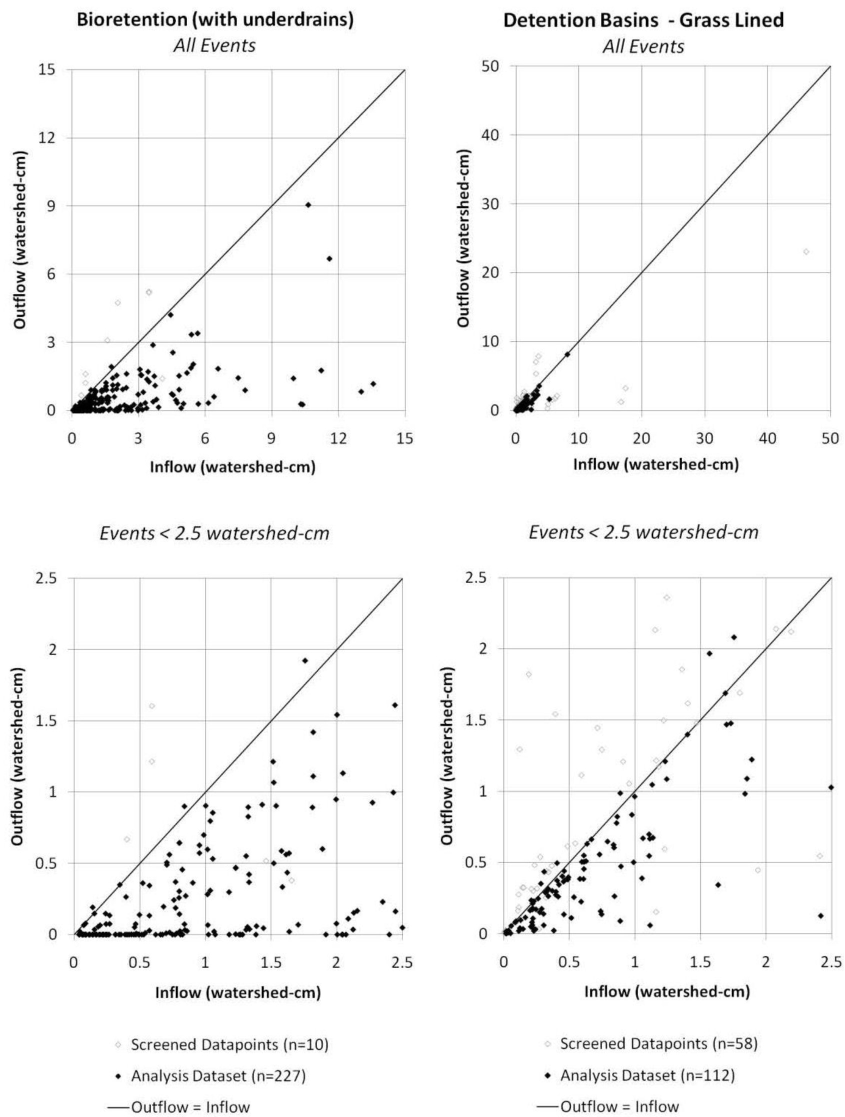
Appendix A

Exhibit 7a. Scatter Plot of Inflow and Outflow Volume



Note: data inventory ("n=##") represents the "all events" scale range.

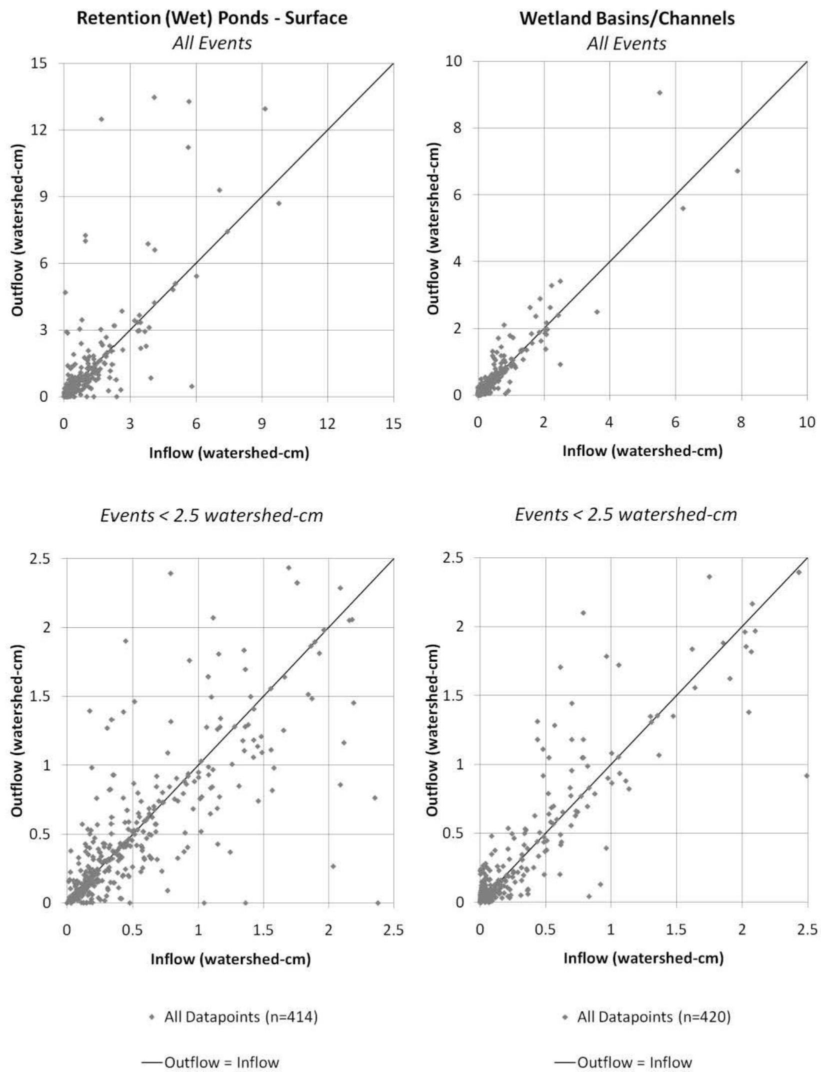
Exhibit 7b. Scatter Plot of Inflow and Outflow Volume



Note: data inventory ("n=##") represents the "all events" scale range.

Exhibit 7c. Scatter Plot of Inflow and Outflow Volume

(Reasonableness Screening Not Conducted for Retention Ponds and Wetland Basins/Channels)



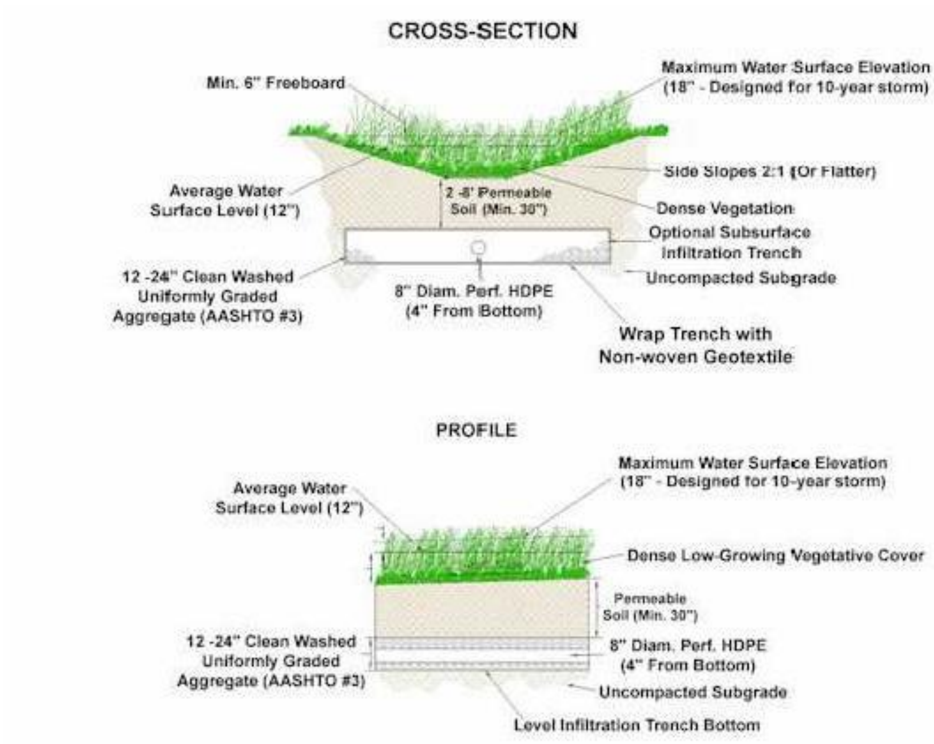
Note: data inventory ("n=##") represents "all events" scale range.

Appendix B

Description

Vegetated swales are broad, shallow channels designed to slow runoff, promote infiltration, and filter pollutants and sediments in the process of conveying runoff. Vegetated Swales provide an environmentally superior alternative to conventional curb and gutter conveyance systems, while providing partially treated (pretreatment) and partially distributed stormwater flows to subsequent BMPs. Swales are often heavily vegetated with a dense and diverse selection of native, close-growing, water-resistant plants with high pollutant removal potential. The various pollutant removal mechanisms of a swale include: sedimentary filtering by the swale vegetation (both on side slopes and on bottom), filtering through a subsoil matrix, and/or infiltration into the underlying soils with the full array of infiltration-oriented pollutant removal mechanisms.

A Vegetated Swale typically consists of a band of dense vegetation, underlain by at least 24 inches of permeable soil. Swales constructed with an underlying 12 to 24 inch aggregate layer provide significant volume reduction and reduce the stormwater conveyance rate. The permeable soil media should have a minimum infiltration rate of 0.5 inches per hour and contain a high level of organic material to enhance pollutant removal. A nonwoven geotextile should completely wrap the aggregate trench (See BMP 6.4.4 Infiltration Trench for further design guidelines).



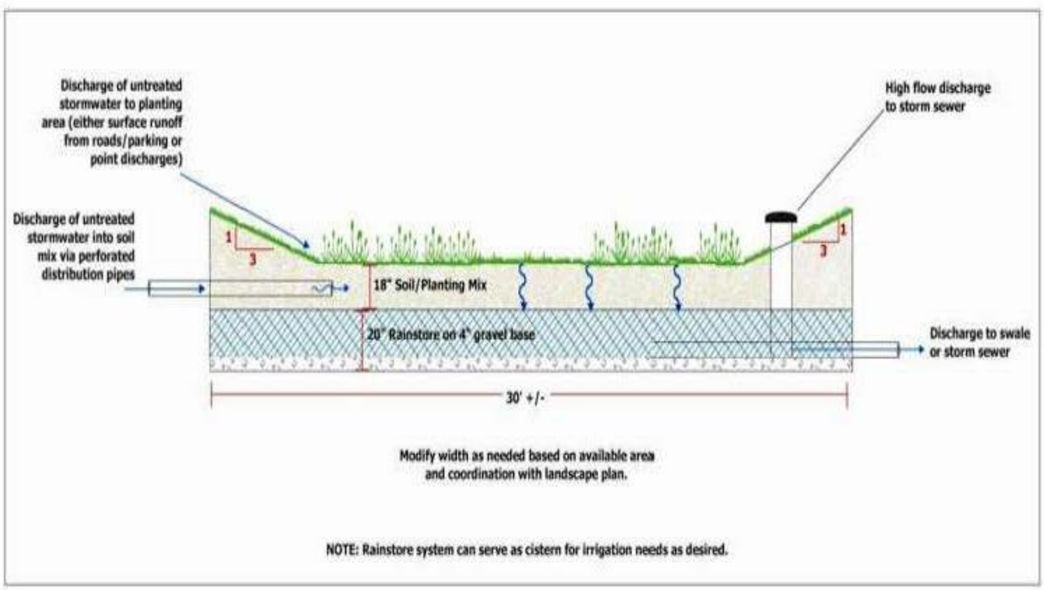
A major concern when designing Vegetated Swales is to make certain that excessive stormwater flows, slope, and other factors do not combine to produce erosive flows, which exceed the Vegetated Swale capabilities. Use of check dams or turf reinforcement matting (TRM) can enhance swale performance in some situations.

A key feature of vegetated swale design is that swales can be well integrated into the landscape character of the surrounding area. A vegetated swale can often enhance the aesthetic value of a site through the selection of appropriate native vegetation. Swales may also discreetly blend in with landscaping features, especially when adjacent to roads.

Variations

Vegetated Swale with Infiltration Trench

This option includes a 12 to 24 inch aggregate bed or trench, wrapped in a nonwoven geotextile (See BMP 6.4.4 Infiltration Trench for further design guidelines). This addition of an aggregate bed or trench substantially increases volume control and water quality performance although costs also are increased. Soil Testing and Infiltration Protocols in Appendix C should be followed.

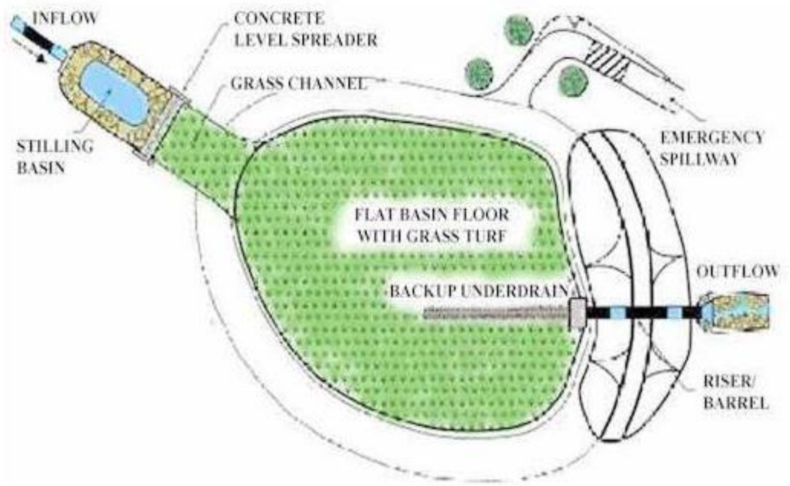


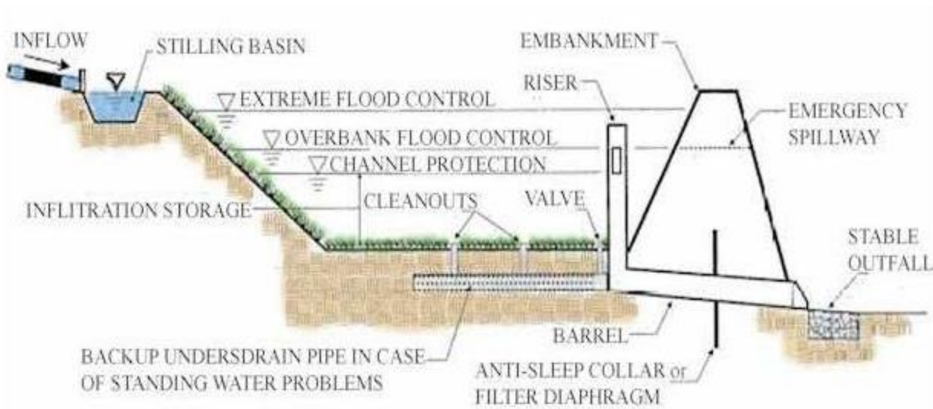
Vegetated Swales with Infiltration Trenches are best fitted for milder sloped swales where the addition of the aggregate bed system is recommended to make sure that the maximum allowable ponding time of 72 hours is not exceeded. This aggregate bed system should consist of at least 12 inches of

Appendix C

Description

Infiltration Basins are shallow, impounded areas designed to temporarily store and infiltrate stormwater runoff. The size and shape can vary from one large basin to multiple, smaller basins throughout a site. Ideally, the basin should avoid disturbance of existing vegetation. If disturbance is unavoidable, replanting and landscaping may be necessary and should integrate the existing landscape as subtly as possible and compaction of the soil must be prevented (see Infiltration Guidelines). Infiltration Basins use the existing soil mantle to reduce the volume of stormwater runoff by infiltration and evapotranspiration. The quality of the runoff is also improved by the natural cleansing processes of the existing soil mantle and also by the vegetation planted in the basins. The key to promoting infiltration is to provide enough surface area for the volume of runoff to be absorbed to meet the criteria in Chapter 3. An engineered overflow structure should be provided for the larger storms.





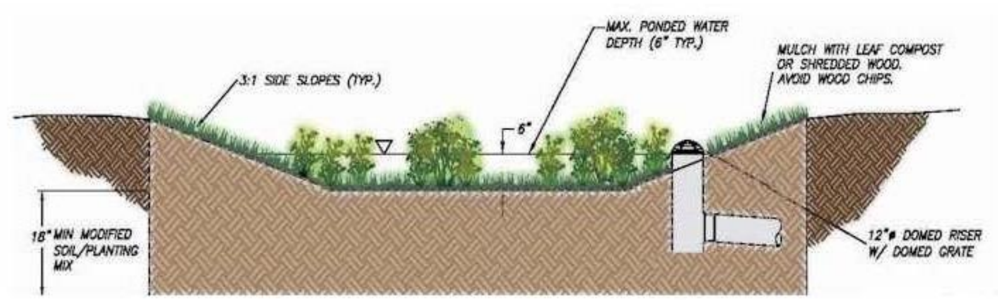
Appendix D

Description

Bioretention is a method of treating stormwater by pooling water on the surface and allowing filtering and settling of suspended solids and sediment at the mulch layer, prior to entering the plant/soil/microbe complex media for infiltration and pollutant removal. Bioretention techniques are used to accomplish water quality improvement and water quantity reduction. Prince George's County, Maryland, and Alexandria, Virginia have used this BMP since 1992 with success in many urban and suburban settings.

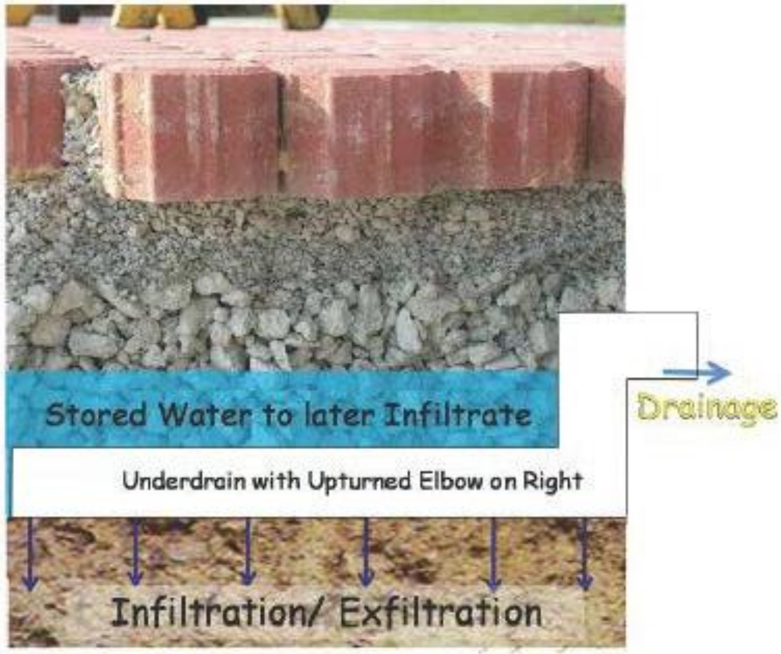
Bioretention can be integrated into a site with a high degree of flexibility and can balance nicely with other structural management systems, including porous asphalt parking lots, infiltration trenches, as well as non-structural stormwater BMPs described in Chapter 5.

The vegetation serves to filter (water quality) and transpire (water quantity) runoff, and the root systems can enhance infiltration. The plants take up pollutants; the soil medium filters out pollutants and allows storage and infiltration of stormwater runoff; and the bed provides additional volume control. Properly designed bioretention techniques mimic natural ecosystems through species diversity, density and distribution of vegetation, and the use of native species, resulting in a system that is resistant to insects, disease, pollution, and climatic stresses.



Rain Gardens / Bioretention function to:

- Reduce runoff volume
- Filter pollutants, through both soil particles (which trap pollutants) and plant material (which take up pollutants)
- Recharge groundwater by infiltration
- Reduce stormwater temperature impacts
- Enhance evapotranspiration
- Enhance aesthetics
- Provide habitat



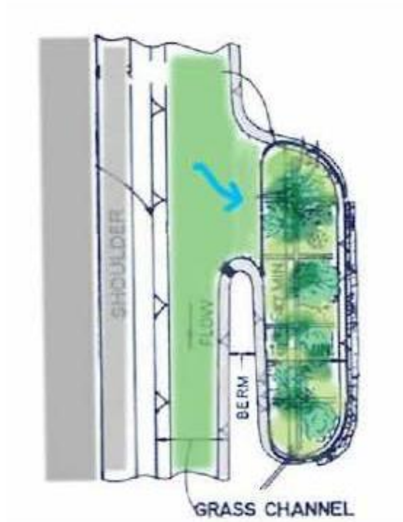
Pavement Location in "Best" In-situ Soil

A developed site may have surprisingly varied underlying soils, some of which will be borderline impermeable while others will have some permeability. If the designer is able to identify locations with somewhat permeable underlying soils, the permeable pavements will potentially infiltrate a substantial amount. It is typically much easier to find permeable in situ soils on the barrier islands, the coastal plain, and sandhills.

Optimizing Evapotranspiration

While permeable pavements typically do not have a substantial amount of ET loss, there are a few pavement types that may hold water near the surface long enough for minor ET losses to occur. A system that captures and stores water near the surface of the pavement, such as CGP and PG filled with sand, has been estimated to temporarily store at least 6 mm of most storms and presumably "release" this water to the atmosphere by ET (Collins et al., 2008a). On an annual basis, up to 33 percent of all precipitation events would be "captured" in this way by these pavements. A similar effect was not found for other types of permeable pavements (PC or PICP filled with gravel).

- **Roads and highways**



- **Parking Lots**
- **Parking Lot Island Bioretention**

- **Commercial/Industrial/Institutional**

In commercial, industrial, and institutional situations, stormwater management and greenspace areas are limited, and in these situations, Rain Gardens for stormwater management and landscaping provide multifunctional options.